

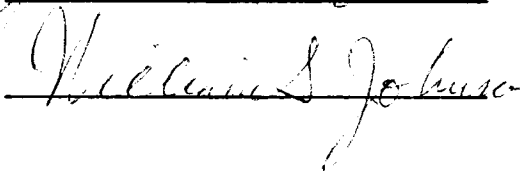
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AN ANALYTICAL AND EXPERIMENTAL INVESTIGATION OF A
GAS-DYNAMIC TECHNIQUE FOR THE CONTINUOUS FEEDING
OF POWDERED SOLIDS TO HIGH-PRESSURE VESSELS

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jose A. Lamas

August 1985

to my parents

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ABSTRACT

The "gas-dynamic injector", a device designed to feed powdered solids in a continuous, well-controlled manner to high-pressure vessels, is investigated analytically and experimentally to determine its feasibility for practical applications. The device operates with a high-pressure primary gas and a low-pressure secondary gas. By expanding the primary gas in a converging-diverging nozzle, a low-pressure region of supersonic flow is created. There, a suspension of solids in secondary gas is injected. After a constant-pressure mixing process occurs, the pressure is raised in a shock wave and a subsonic diffuser. The assumption that the gaseous and solid phases in the mixture are always in equilibrium allows the flows to be mathematically modeled as frictionless, one-dimensional flows of an ideal gas. Results from a parametric study show that the practical application of the gas-dynamic injector for the feeding of powdered coal to combustors operating at pressures on the order of 18 bar is possible. The experimental study, which was conducted to verify the mathematical model, indicates that viscous friction needs to be accounted for in future analyses.

TABLE OF CONTENTS

CHAPTER	PAGE
1. INTRODUCTION	1
2. THE GAS-DYNAMIC INJECTOR	4
Principle of Operation	4
Description of Components	4
Special Features of the Flow in a Gas-Dynamic Injector	8
3. A REVIEW OF SOME RELEVANT CONCEPTS IN THE	
FLUID MECHANICS OF GAS-SOLIDS SUSPENSIONS	10
Gas-Solids Suspensions in Thermodynamic Equilibrium	10
Some Relevant Properties of a Gas-Solids Suspension	13
The Equilibrium and Frozen Speeds of Sound	14
Partly- and Fully-Dispersed Shock Waves in a Gas-Solids	
Suspension	17
Criterion for the Existence of a Partly-Dispersed Shock	
Wave in a Gas-Dynamic Injector	21
4. A SIMPLIFIED MATHEMATICAL MODEL OF A GAS-DYNAMIC INJECTOR . . .	22
Assumptions Considered in the Theoretical Analysis	24
Derivation of the Governing Equations	25
Summary of the Analytical Model	38
Minimum Possible Value of the Exit/Injection Pressure	
Ratio Which Allows the Existence of a Partly-Dispersed	
Shock in the Gas-Dynamic Injector	41
Maximum Possible Value of the Exit/Injection Pressure	
Ratio for Which the Flow Can Be Established in the	
Gas-Dynamic Injector	42
5. A PARAMETRIC STUDY OF THE GAS-DYNAMIC INJECTOR FOR A TYPICAL	
APPLICATION	45
Values of the Design Variables for the Parametric Study . . .	47
Discussion of Results	48
6. THE EXPERIMENTAL STUDY	65
Design of the Test Section	65
Selection of Test Conditions	71
Instrumentation and Data Acquisition	74
Evaluation and Development of the Experimental	
Apparatus and Techniques	76
Experimental Results	85
7. SUGGESTED PROCEDURE FOR MODIFYING THE THEORETICAL RESULTS TO	
TO DESIGN AN ACTUAL GAS-DYNAMIC INJECTOR	95
8. CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH	99

CHAPTER	PAGE
REFERENCES	101
APPENDICES	104
A. COMPUTER PROGRAM USED IN THE PARAMETRIC STUDY	105
B. FLOW DIAGRAM OF PROGRAM GDI	117
C. NUMERICAL RESULTS OF THE PARAMETRIC STUDY	122
D. DERIVATION OF THE APPROXIMATED STRAIGHT-LINE EQUATION WHICH GIVES THE MAXIMUM VALUE OF THE RATIO OF VESSEL INLET PRESSURE TO INJECTION PRESSURE	131
E. COMPUTER PROGRAM USED FOR THE EXPERIMENTAL MODEL DESIGN	135
F. TEST FACILITY	148
G. COMPUTER PROGRAM USED FOR EXPERIMENTAL DATA ACQUISITION	165
H. EXPERIMENTAL PRESSURE READINGS ALONG THE INJECTOR	190
I. UNCERTAINTY ANALYSIS	194
J. ESTIMATION OF THE INJECTION PRESSURE	199
VITA	201

LIST OF FIGURES

FIGURE	PAGE
1.1. Some Conventional Solids Feeders	2
2.1. The Gas-Dynamic Injector	5
2.2. Pressure Distribution Along the Longitudinal Axis of the Gas-Dynamic Injector	7
3.1. Mixing Process of Particles and Gas Having the Same Temperature	15
3.2. The Structure of a Partly-Dispersed Shock Wave in a Gas-Solids Suspension	18
4.1. Gas-Dynamic Injector Model Used in the Theoretical Analysis	23
4.2. Control Volume for the Mixing Region	34
5.1. Schematic Representation of the Process of Pressurized Coal Combustion Applied to Power Generation	46
5.2. P_{g1}/P_4 as a Function of N_{g1} and N_{g2}	50
5.3. Maximum Possible Value of P_4/P_e as a Function of N_{g1} and N_{g2}	52
5.4. Effect the Variation of N_{g1} and N_{g2} on the Lower Limit of P_4/P_e Which Allows the Formation of a Partly-Disperse Shock	54
5.5. Theoretical Limiting Values for N_{g1} and P_4/P_e	55
5.6. Effect of Variation of N_{g2} on A_e	57
5.7. Effect of the Variation of N_{g1} and N_{g2} on the Area Ratio A_4/A_e	58
5.8. P_{g1}/P_4 as a Function of N_{g1} and P_e for $N_{g2}=1$ and $T_{0e}=700^\circ K$.	59
5.9. P_{g1}/P_4 as a Function of N_{g1} and T_{0e} for $N_{g2}=1$ and $P_e=1$ bar .	61
5.10. Behaviour of the Parameters A^*/A_e , A_1/A_e , A_2/A_e , A_4/A_e , P_{g1}/P_4 , and $[P_4/P_e]_{(max)}$ for $N_{g2}=1$, $T_{0e}=700^\circ K$, $P_4/P_e=18$, $P_e=1$ bar	62
6.1. Schematic View of the Gas-Dynamic Injector Modified for the Experimental Investigation	66

FIGURE	PAGE
6.2. Side View of Assembled Test Section	67
6.3. Cutaway View of Test Section	68
6.4. Injection Tube Dimensions	70
6.5. Experimentally-Determined Pressure Distribution for Gas-Dynamic Injector with Experimental Values of Cross-Sectional Areas and Mass Flow Rates Closely Matching Theoretical Values	79
6.6. Pressure Distrbution for Gas-Dynamic Injector Having Theoretically-Computed Cross-sectional Areas and an Overpressurized Stagnation Chamber	81
6.7. Pressure and Mach Number Distributions for Flows with and without Friction (— : Frictionless Flow, ---- : Flow with Friction)	83
6.8. Pressure Distribution for Gas-Dynamic Injector Having a Modified Channel Contour with Theoretical Values of Mass Flow Rates and Stagnation Pressure of Primary Air	88
6.9. Schlieren Photographs of the Pseudo-Shock	90
6.10. Schlieren Photograph of the Jet of Gas-Solids Suspension . .	92
6.11. Geometric Characteristics of the Flow Field in the Region of Gas-Solids Jet Injection	93
7.1. Comparison between Theoretical and Actual Distributions of Cross-Sectional Areas, Pressures, and Mach Numbers in the Gas-Dynamic Injector	96
F.1. Schematic View of the Gas-Dynamic Injector Test Facility . .	150
F.2. The Test Facility	152
F.3. Scanivalve	155
F.4. Magnetic Feeder Controller and Internal Circuit	157
F.5. Diagram of Pressure Lines and Thermocouple Connections . . .	158
F.6. Pressure Ports and Temperature Channels	159
F.7. Low-Pressure Differential Solids Feeder	162

LIST OF TABLES

TABLE	PAGE
4.1. List of Independent Equations in the Analytical Model . . .	39
4.2. List of Unknowns	40
5.1. Data Used in the Parametric Study	49
5.2. Parameters A^*/A_e , A_1/A_e , A_2/A_e , A_4/A_e , P_{g1}/P_4 , A_e , $[P_4/P_e]_{(max)}$, $[P_4/P_e]_{(min)}$ as Functions of the Primary Gas Nondimensional Mass Flow Rate N_{g1} in the Range $7.5 < N_{g1} < 7.9$	63
6.1. Fixed Parameters Used in the Experimental Study	73
6.2. Theoretical Results of Parameters Independent of the Total Temperature for $T_{0e}/T_{g1}=1$	75
6.3. Values of the Mass Flow Rates and Solids Volume Fraction as Functions of T_{g1} for $T_{0e}/T_{g1}=1$	75
6.4. Experimental Values of the Mass Flow Rates, Temperatures, and Total Pressure in the Stagnation Chamber for Nozzle Designed with Theoretically-Computed Values	77
6.5. Mass Flow Rates and Temperatures Measured During Test Using Theoretically-Computed Cross-Sectional Areas and Higher-than-Theoretical Value of Pressure in the Stagnation Chamber	80
6.6. Mass Flow Rates, Temperatures, Nozzle Dimensions, and Pressures Measured During Test Using Modified Contour . . .	86
6.7. Comparison between Theoretical and Modified Cross-Sectional Areas	89
C.1. Pressure Ratio P_{g1}/P_4 as a Function of the Primary and Secondary Air Mass Flow Parameters N_{g1} and N_{g2}	123
C.2. Maximum Value of P_4/P_e ($[P_4/P_e]_{(max)}$) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	124
C.3. Minimum Value of P_4/P_e ($[P_4/P_e]_{(min)}$) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	125

TABLE	PAGE
C.4. Injection Tube Exit Area (A_e) as a Function of the Parameter N_{g2}	125
C.5. Ratio of Throat Cross-Sectional Area to Injection Tube Exit Area (A^*/A_e) as Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	126
C.6. Ratio of Cross-Sectional Area at Section '1' to Injection Tube Exit Area (A_1/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	127
C.7. Ratio of Cross-Sectional Area at Section '2' to Injection Tube Exit Area (A_2/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	128
C.8. Ratio of Cross-Sectional Area at Section '4' to Injection Tube Exit Area (A_4/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}	129
C.9. Effect of Change of P_e on the Parameter P_{g1}/P_4	130
C.10. P_{g1}/P_4 as a Function of T_{0e}/T_{g1}	130
H.1. Pressure Readings for Test with Theoretically-Computed Nozzle Contour and Design Values of the Mass Flow Rates . .	191
H.2. Pressure Readings During Test with Overpressurized Stagnation Chamber and Theoretically-Computed Cross-Sectional Areas	192
H.3. Pressure Readings Corresponding to the Test with a Modified Nozzle Block Contour	193
I.1. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air and Secondary Air for Test with Theoretically-Determined Contour and Design Values of Mass Flow Rates	197
I.2. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air for Test with Theoretically-Determined Contour and $P_{g1} = 4.394$ bar .	197

TABLE

PAGE

I.3. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air and Secondary Air for Test with Modified Channel Contour	198
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NOMENCLATURE

ρ	: Gas Density
ψ	: Solids Mass Fraction
ϵ	: Solids Volume Fraction
η	: Solids Loading Ratio
γ	: Gas Specific Heat Ratio
τ	: Reference Time
a	: Speed of Sound
A	: Area
A'	: Actual Cross-Sectional Area
a_{eq}	: Equilibrium Speed of Sound
B	: Vertical Spacing between Upper and Lower Nozzle Blocks
c	: Particle Specific Heat
c_p	: Constant-Pressure Specific Heat of the Gas
c_v	: Constant-Volume Specific Heat of the Gas
c_{pe}	: Constant-Pressure Specific Heat of Gas-Solids Suspension at Section 'e'
c_{pm}	: Constant-Pressure Specific Heat of Mixture at Sections '2', '3', '4'
c_{ps}	: Constant-Pressure Specific Heat of the Gas-Solids Suspension
d	: Density of Particles
D_h	: Hydraulic Diameter
D_p	: Diameter of Particles
M	: Mach Number

M_{eq}	: Mach Number of Mixture at Equilibrium Conditions
M_f	: Mach Number of Mixture at Frozen Conditions (Mach Number of the Gas Phase)
M'	: Actual Mach Number
$\dot{m}_e$	: Mass Flow Rate at Section 'e'
$\dot{m}_{g1}$	: Mass Flow Rate of Primary Gas
$\dot{m}_{g2}$	: Mass Flow Rate of Secondary Gas
$\dot{m}_p$	: Mass Flow Rate of Particles
$\dot{m}_t$	: Total Mass Flow Rate
N_{g1}	: Ratio of Mass Flow Rate of Primary Gas to Mass Flow Rate of Particles
$N_{g1(min)}$	: Minimum Value of N_{g1}
$N_{g1(crit)}$	: Critical Value of N_{g1}
N_{g2}	: Ratio of Mass Flow Rate of Secondary Gas to Mass Flow Rate of Solids
P	: Pressure
$[P_4/P_e]_{(crit)}$	: Critical Value of P_4/P_e Which Gives an Absolute Minimum for N_{g1}
$[P_4/P_e]_{(max)}$	: Maximum Value of P_4/P_e for the Operation of the Gas-Dynamic Injector
$[P_4/P_e]_{(min)}$	: Minimum Value of P_4/P_e Which Allows the Existence of a Partly-Dispersed Shock
P_{g1}	: Total Pressure of Primary Gas in Stagnation Chamber
P'	: Actual Static Pressure
P'_0	: Actual Stagnation Pressure
R	: Ideal Gas Constant

R_e	: Equivalent Ideal Gas Constant of Gas-Solids Suspension at Section 'e'
R_m	: Equivalent Ideal Gas Constant of Mixture at Sections '2', '3', and '4'
R_s	: Equivalent Ideal Gas Constant of a Gas-Solids Suspension
T_g	: Static Temperature of Gas
T_{g1}	: Total Temperature of Primary Gas
T_{g2}	: Total Temperature of Secondary Gas
T_p	: Temperature of Particles
t_f	: Flow Time
U	: Velocity
U_a	: Velocity of the Mixture at Equilibrium Upstream of a Shock Front
U_b	: Velocity of the Gas Phase at Frozen Conditions Past a Disturbance in the Flow
U_c	: Velocity of the Mixture at Equilibrium Downstream of a Shock Front
U_g	: Velocity of Gas
U_p	: Velocity of Particles

Subscripts

0	: General Stagnation Conditions
1	: Section '1'
2	: Section '2'
3	: Section '3'
4	: Section '4'

e	: Section 'e'
eq	: Equilibrium Conditions
g	: Gas
g1	: Primary Gas (Gas 1)
g2	: Secondary Gas (Gas 2)
p	: Particles
s	: Gas-Solids Suspension

Superscripts

*	: Throat
'	: Actual Conditions

Abbreviations

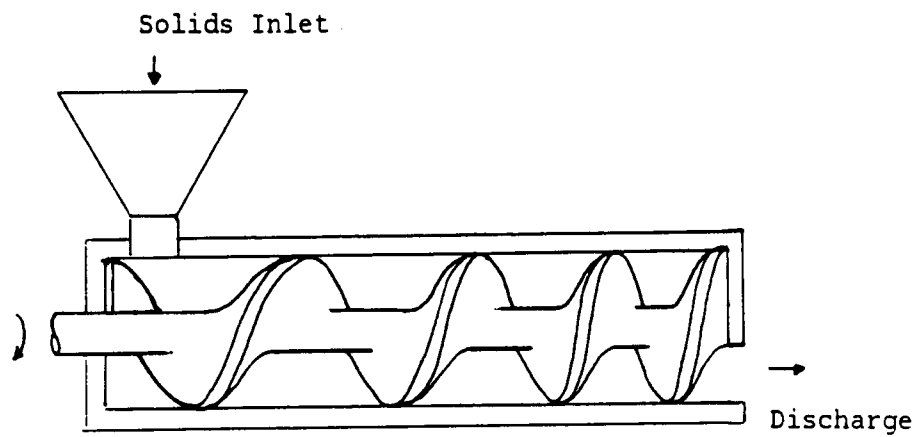
(crit)	: Critical Conditions
GDI	: Gas-Dynamic Injector
(est)	: Estimated
(ext)	: External
(max)	: Maximum
(min)	: Minimum
MHD	: Magnetohydrodynamic
PFBC	: Pressurized Fluidized-Bed Combustion
SCFM	: Standard Cubic Feet per Minute
psi	: Pounds per Square Inch
psig	: Pounds per Square Inch (gage)

CHAPTER 1

INTRODUCTION

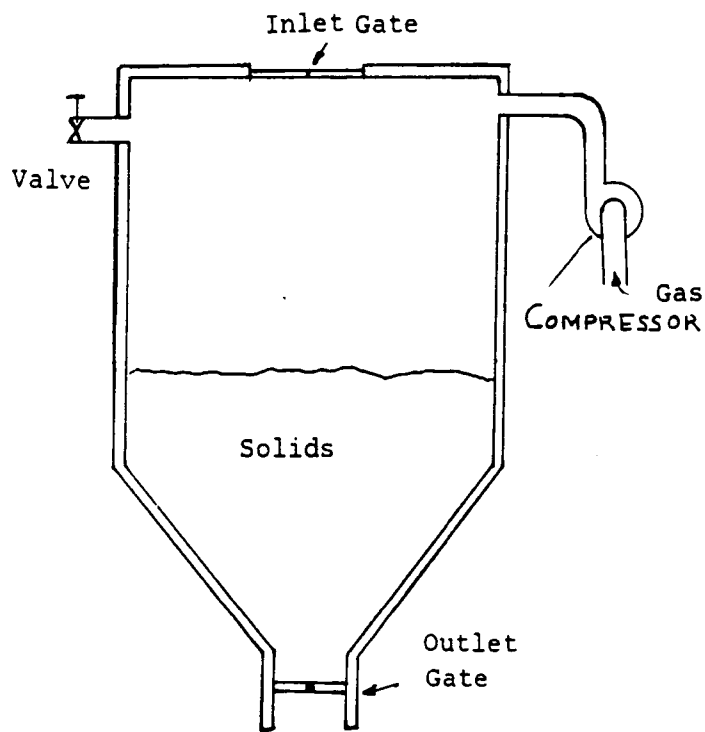
Modern coal gasification and coal-fired power plants require the development of solids feeding systems capable of delivering dry, pulverized coal in a continuous and well-controlled manner to reactors operating at pressures as high as 70 bar. Unlike liquids or gases, which can be handled by conventional pumps or compressors, pulverized solids can only be handled by specially designed solids feeding systems. Figure 1.1 shows some conventional solids feeders presently used. Extrusion (screw) feeders, are capable of delivering the solids in a continuous manner, but their use is limited to pressure differentials not above 5 bar because of problems with solids compactation. Other feeders such as lock-hopper feeders can deliver solids at higher pressures, but not in a continuous manner. Rotary feeders can deliver the solids in an intermittent manner at pressure differentials not above 2 bar.

Major problems observed in conventional feeders include the excessive wear of close-tolerance moving parts, such as that which occurs in screw feeders and rotary feeders, and the excessive deterioration of valves and seals that occurs in lock-hopper feeders. Thus, there is a need to develop a feeder which has no moving parts in direct contact with the solids and that can feed the solids in a continuous manner to high-pressure vessels.

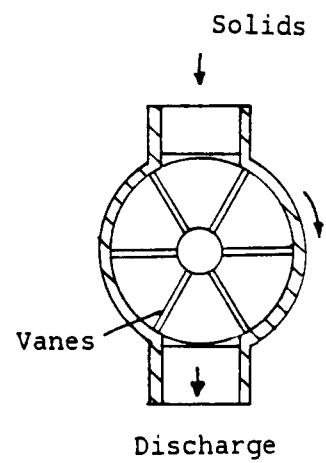


SCREW FEEDER

(Pressure Differential 4 bar max.)



LOCK-HOPPER FEEDER



(Pressure Differential 2 bar max.)

Figure 1.1. Some Conventional Solids Feeders

A new solids feeding technique, called "gas-dynamic injection", was investigated in this project. The technique was originally proposed by Dr. R. J. Krane in 1974 [1]. The purpose of this research was to determine the practical feasibility of a solids feeder using such a technique which is called the "gas-dynamic injector" (GDI). This was accomplished by performing both analytical and experimental investigations of the device. A simple mathematical model was constructed and used to perform a parametric study. Then, an experimental device, which is based on the mathematical model was built and tested for verification. This required the modification and instrumentation of a previously developed test facility.

A full description of the gas-dynamic injector is presented in Chapter 2. A review of the basic concepts of gas-solids suspensions used in the mathematical model is presented in Chapter 3. The formulation of the mathematical model is in Chapter 4. The parametric study is presented in Chapter 5. The experimental investigation, which includes the design and testing of the GDI model, is discussed in Chapter 6. A procedure suggested for modifying the theoretical results to design an actual GDI is in Chapter 7. Finally, the conclusions and some recommendations for further investigation are presented in Chapter 8.

CHAPTER 2

THE GAS-DYNAMIC INJECTOR

Principle of Operation

The principle of operation of the gas-dynamic injector (GDI) is based on the ability of compressible fluid flows to undergo compression and expansion processes such that solid particles moving within the fluid can be transported from a region of low pressure to a region of high pressure. The idea behind the operation of this device is to expand a high-pressure gas to supersonic conditions in order to create a low-pressure region into which the solids (in a gas-solids suspension) can be injected. A mixing process then occurs between the two streams such that the resulting solids-gas mixture attains a supersonic speed. The mixture is then passed through supersonic and subsonic diffusers where its pressure is increased to that of the high-pressure vessel being fed.

Description of Components

A schematic representation of the gas-dynamic injector is shown in Figure 2.1. The basic components are a supersonic (converging-diverging) nozzle, an injection tube, a mixing section, a supersonic diffuser, and a subsonic diffuser. The device operates with a source of high-pressure primary gas and a source of low-pressure secondary gas. The solids are mixed with the secondary gas to create a low-pressure gas-solids suspension which is carried by the injection tube into the

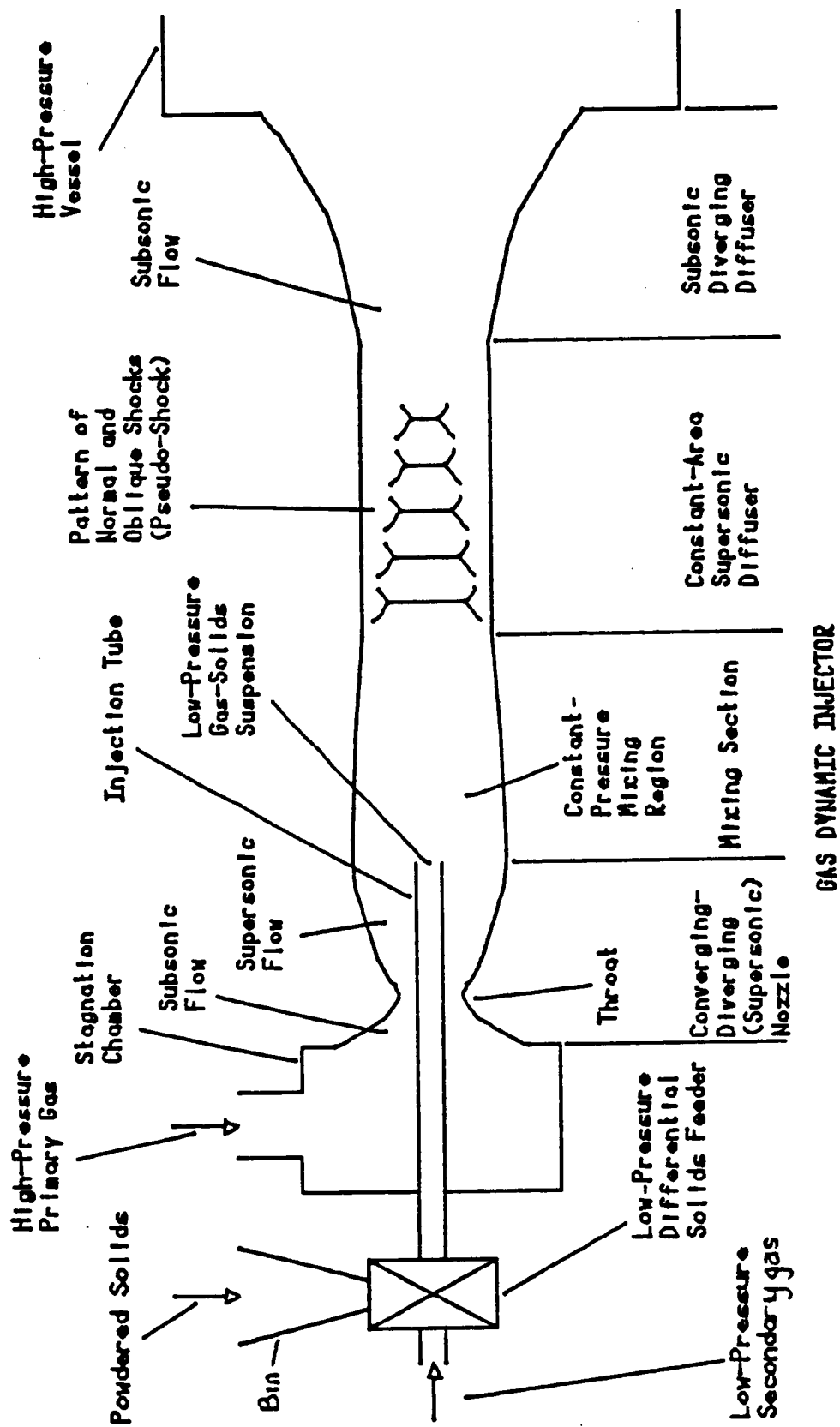


Figure 2.1. The Gas-Dynamic Injector

mixing section of the device. The primary gas is fed into the stagnation chamber. It then enters the converging-diverging nozzle where it expands and accelerates, reaching supersonic speeds in the diverging section of the nozzle. Once the primary gas has been expanded to meet the pressure conditions of the gas-solids suspension, it is discharged into the mixing section. The injection tube extends along the longitudinal axis of the GDI through the subsonic region, the throat, and supersonic region of the nozzle to discharge the gas-solids suspension into the mixing section as a co-flowing jet configuration. The two streams undergo a constant-pressure mixing process. The condition of constant-pressure mixing between the two streams helps prevent the formation of shock waves during the process. After sufficient mixing occurs between the two streams, to ensure that the resulting mixture is entirely supersonic, the flow is decelerated; first in a constant-area-type supersonic diffuser and then in a subsonic (diverging) diffuser.

The pressure distribution along the gas-dynamic injector is shown in Figure 2.2. The figure shows that the gas-solids suspension enters the mixing section at the pressure of the injection tube exit section (P_e) and that the mixture exits the subsonic diffuser at the pressure of the high-pressure vessel (P_4). The ratio of these two pressures corresponds to the exit/injection pressure ratio of the device, (P_4/P_e).

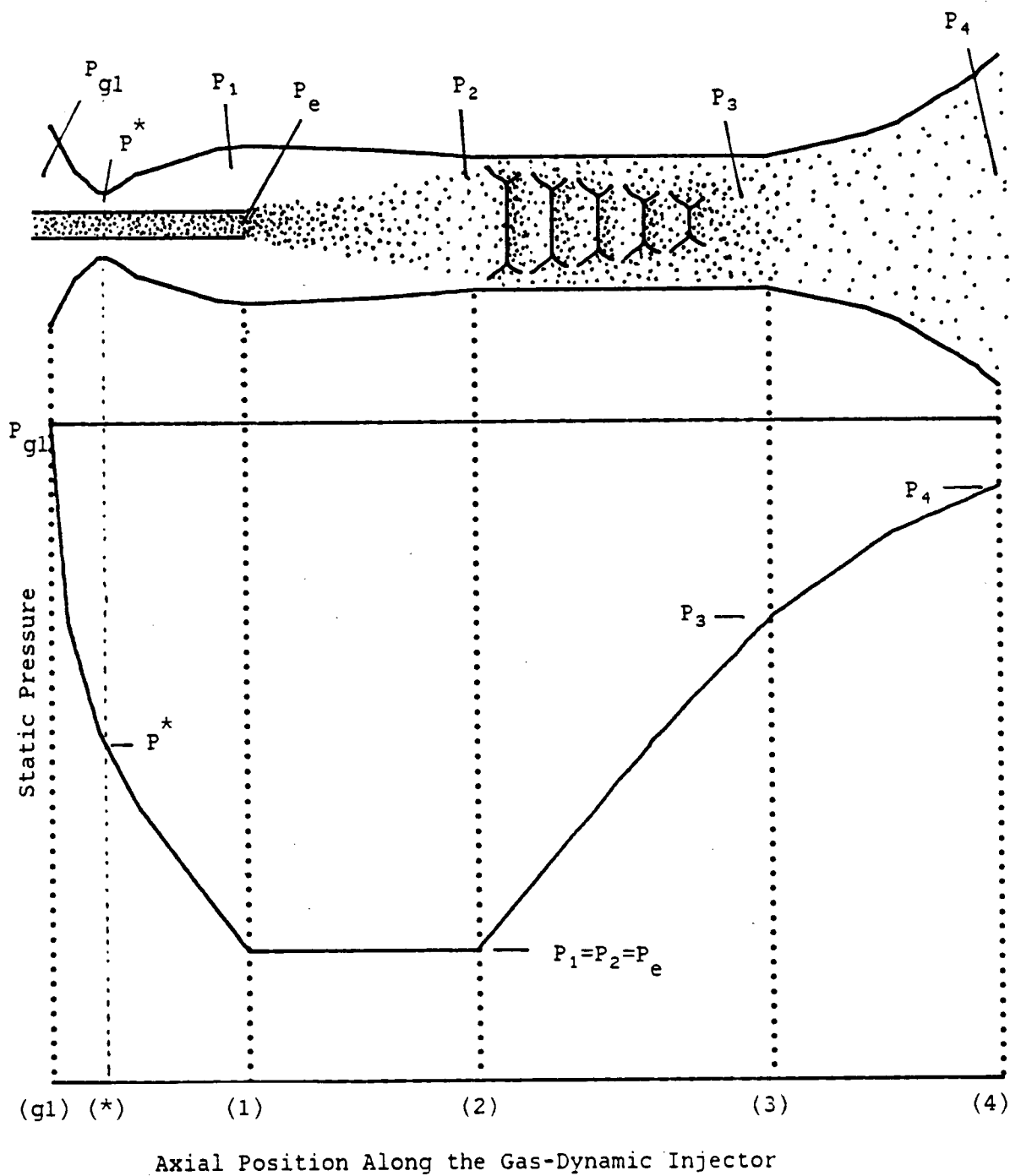


Figure 2.2. Pressure Distribution Along the Longitudinal Axis of the Gas-Dynamic Injector

Special Features of the Flow in a Gas-Dynamic Injector

Discharge of Injection Tube

During the solids injection process, the flow of gas-solids suspension in the injection tube should discharge at conditions such that the speed of the suspension is less than the speed of sound of the gas phase. This is done in order to prevent the formation of expansion or compression waves at the exit section of the injection tube. The presence of these waves would not allow matching between exit and back pressure [12]. Expansion waves may be present when the sonic or supersonic gas flow issuing from a duct is not expanded to the correct back pressure. Compression waves are present when a supersonic stream discharges at a pressure which is below the back pressure at the exit section.

As indicated by Rudinger [20,21] and Boothroyd [22], a gas-particle mixture reaches sonic conditions (based on the speed of sound of the mixture) at lower speeds than the flow of gas without particles. Thus, the Mach number of the mixture in the injection tube exit plane can be unity without having shocks or expansion waves at the exit section of the injection tube.

The Supersonic Diffuser

The constant-area-type supersonic diffuser was selected because it will not present serious erosion problems due to particle-wall collisions as in converging supersonic diffusers, it requires no moving

parts, does not present starting problems (as would a variable-area-type supersonic diffuser), and has good stability characteristics [13,14,15].

Supersonic-Subsonic Transition

In real flows the transition from supersonic to subsonic flow in constant-area ducts does not occur through a single normal shock as predicted by simple one-dimensional theory. Instead, it occurs through a series of successive compressions along the duct in a complicated pattern of normal and oblique shocks known as a "pseudo-shock" [24]. This phenomenon is attributed to the presence of the boundary layer in which the flow is subsonic (having zero velocity at the wall). In order to match the subsonic conditions inside the boundary layer, the normal shock splits into two diverging oblique shocks inside this region giving the shape shown in Figure 2.2. Because the pressure increases across the shocks, the boundary layer separates and interacts with the flow downstream of the shock. As a result of the reduced flow area, the subsonic flow downstream of the normal section of the shock accelerates again to supersonic conditions. Then, another shock is formed downstream from the previous one. This process is repeated until the entire flow is sonic or subsonic and the result is the pattern observed in the same figure. An interesting aspect of pseudo-shocks is that the overall pressure rise across the series of shocks is closely predicted by the one-dimensional theory for a single normal shock [15,16]. Thus, even though the flow in a real gas-dynamic injector will encounter a pseudo-shock, the analytical model will assume that the flow passes through a single normal shock.

CHAPTER 3

A REVIEW OF SOME RELEVANT CONCEPTS IN THE FLUID MECHANICS OF GAS-SOLIDS SUSPENSIONS

Rudinger [20,21] and Boothroyd [22] studied the behaviour of a gas-particle mixture from a thermodynamic standpoint. Such studies involve the derivation of the basic equations used for the determination of the thermodynamic state of a mixture in a steady-state, equilibrium condition. The derivation of these equations assumes that the particles are spheres of uniform size which are equally distributed throughout the gas; they do not exchange mass but only heat and momentum with the surrounding gas. It is assumed that no chemical reactions take place either in the gas phase or in the solids phase. It is also assumed that the gas is an ideal gas and that the specific heats of the gas and particles are constants.

Gas-Solids Suspensions in Thermodynamic Equilibrium

The conditions for the suspension to be in a thermodynamic equilibrium state are that both the gas and solid phases must have the same temperatures and velocities; that is, $T_p = T_g \equiv T$ and $U_p = U_g \equiv U$. Under these conditions, the solids mass fraction and the solids loading ratio are constants given by

$$\psi = \frac{\dot{m}_p}{(\dot{m}_p + \dot{m}_g)} \quad (3.1)$$

and

$$\eta = \frac{\dot{m}_p}{\dot{m}_g} \quad (3.2)$$

respectively.

The contribution of the random motion of the particles to the total pressure is a function of the particle diameter and not of the solids volume fraction. The partial pressure due to the random motion of the particles is less than 1 percent of the total pressure when the particle diameter is greater than a few hundredths of a micrometer [20]. Since the solid particle sizes of interest in the present study are typically several orders of magnitude larger, the static pressure in the suspension is the pressure given by the equation of state for the gas phase:

$$P = \rho R T \quad (3.3)$$

This equation can be written in terms of the solids volume fraction, the density of the mixture, and the solids loading ratio as:

$$P = \frac{\rho_s R T}{(1-\epsilon)(1+\eta)} \quad (3.4)$$

Thus, for a fixed solids loading ratio, η , the pressure is a function of the temperature, T , the suspension density, ρ_s , and the solids volume fraction, ϵ . The presence of the solids volume fraction as an additional variable in the equation of state leads to the conclusion that a gas-solids suspension does not follow the ideal gas equation of state. However, the solids volume fraction can be neglected if it is sufficiently small with respect to unity and the behaviour of the

mixture can be approximated by the ideal gas equation, the mixture being treated as a perfect gas with modified properties. The resulting equation of state for this suspension is

$$P = \rho_s R_s T \quad (3.5)$$

where R_s is the modified "gas constant" for the suspension given by

$$R_s = \frac{R}{(1+\eta)} \quad (3.6)$$

R_s is a constant for a fixed solids loading ratio. Thus, the thermodynamic state of the mixture is fully determined by specifying four variables, namely, the pressure, the temperature, the suspension density, and the solids loading ratio.

Care must be taken when employing the above approximation since considerable errors may result in the computed velocity if ϵ is too large to be neglected. For instance, neglecting a volume fraction $\epsilon = .01$ at a solids loading ratio $\eta = 10$ leads to a computed velocity 25 percent below the correct value [20]. The solids volume fraction may be neglected if the solids mass fraction is less than 1/2 ($\psi < .5$), or the solids loading ratio is less than 1 ($\eta < 1$), and the solids-to-gas density ratio (d/ρ) exceeds a value of 1000. The solids volume fraction is computed by using the equation

$$\epsilon = \frac{1}{(d/(\rho\eta) + 1)} \quad (3.7)$$

which may be approximated by

$$\epsilon = \eta(\rho/d) \quad (3.8)$$

when $d/(\rho\eta) \gg 1$. In general, the equilibrium limit is applicable when $\epsilon < .001$.

Some Relevant Properties of a Gas-Solids Suspension

Specific Heat Ratio

Isentropic changes of the mixture follow the relation

$$P(\rho_s)^{-\gamma_s} = \text{constant} . \quad (3.9)$$

The ratio of specific heats for the mixture, γ_s , is determined by

$$\gamma_s = \gamma \frac{(1 + \gamma(c/c_p))}{(1 + \gamma\eta(c/c_p))} \quad (3.10)$$

where:

γ = ratio of specific heats (c_p/c_v) for the gas and

c/c_p = the ratio of the specific heat of the solid to the constant pressure specific heat of the gas.

This isentropic relation assumes that both heat and momentum exchanges are reversible processes. It is important to note that isentropic changes in the mixture are not affected by the solids volume fraction; they depend only on the solids loading ratio and specific heats of each phase. Also note, that the ratio of specific heats for the mixture is always smaller than the ratio of specific heats for the gas and its upper limit is the ratio of specific heats for the gas itself. This condition occurs when $\eta=0$ (no solids are present).

Constant-Pressure Specific Heat

The constant pressure specific heat for a suspension is determined by performing an energy balance on the system shown in Figure 3.1. For an adiabatic mixing process the energy balance states that

$$\dot{m}_g c_p T + \dot{m}_p c T = c_{ps} (\dot{m}_g + \dot{m}_p) T \quad (3.11)$$

After solving for c_{ps} (the constant pressure specific heat of the suspension) and replacing $\dot{m}_p/\dot{m}_g$ by η , the following expression is obtained:

$$c_{ps} = c_p \frac{(1 + (c/c_p))}{(1 + \eta)} \quad (3.12)$$

The constant pressure specific heat for the mixture in thermodynamic equilibrium, like the specific heat ratio of eq. (3.10), is a function of the solids loading ratio and the properties of the solid and gas.

The Equilibrium and Frozen Speeds of Sound

In general, the gas and the solid particles at any point in a flowing mixture may have different velocities and temperatures. Given sufficient time, however, momentum exchange and heat transfer between the gas and particles will result in the equilibration of their velocities and temperatures, respectively. For the purpose of this discussion, assume that the periods required for the equilibration of both velocities and temperatures may be characterized by a single reference time, τ . Comparison of the equilibration time, τ , with a characteristic "flow time", t_f , (the time required by a typical fluid

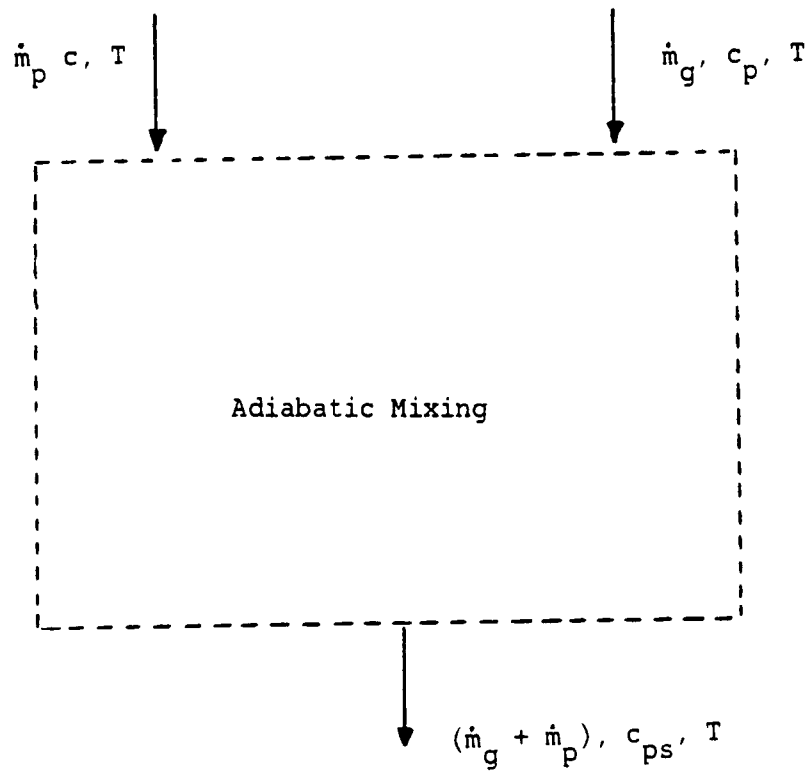


Figure 3.1. Mixing Process of Particles and Gas Having the Same Temperature

particle to traverse that part of the flow field of interest) leads to two important limiting cases of the equilibration processes. When the equilibration time is much larger than the flow time ($\tau/t_f \rightarrow \infty$), there is essentially no exchange of momentum or thermal energy between the gas and the particles; that is, the gas flow is completely unaffected by the presence of the particles and vice versa. This is the limiting case of "frozen flow". However, if the equilibration time is much smaller than the flow time ($\tau/t_f \rightarrow 0$), the other limiting case of "equilibrium flow" occurs. In the equilibrium limit, the equilibration of velocities and temperatures takes place instantaneously at every point in the flow.

The approach to the equilibrium limit can be made arbitrarily close in practice. Imagine that for a given solids loading ratio, η , the solid phase is divided into an ever larger number of smaller and smaller particles. In this limit, the mass and thermal capacity of each particle become so small that the time required for the velocity and temperature of the particle to equilibrate with those of the gas approaches zero. Thus in the equilibrium limit, when the gas phase is ideal and $\epsilon \ll 1$, the mixture itself behaves like an ideal gas with a molecular weight larger than that of the gas phase alone.

Computation of the flow in a gas-dynamic injector requires expressions for the speed of sound in both the frozen and equilibrium limits. Since the gas phase in a frozen flow is completely unaffected by the presence of particles, the appropriate speed of sound for a frozen flow is just the speed of sound for the gas alone, which is given by

$$a_f = \sqrt{\gamma R T} \quad . \quad (3.13)$$

The appropriate speed of sound for an equilibrium flow is given by Rudinger [20] as

$$a_{eq} = a_f \sqrt{\frac{\gamma_s}{\gamma} \frac{1}{(1 + \eta)(1 - \epsilon^2)}} \quad (3.14)$$

Note that, since $\gamma > \gamma_s$ and $(1 + \eta) > 1$, the equilibrium speed of sound, a_{eq} , is less than the frozen sound speed, a_f , when $\epsilon \ll 1$. Also note that a_{eq} decreases as the gas becomes more heavily laden with particles. Substituting eqs. (3.6) and (3.13) in eq. (3.14) gives the required equilibrium sound speed for the mixture in the limit of $\epsilon \ll 1$ as:

$$a_{eq} = \sqrt{\gamma_s R_s T} \quad (3.15)$$

Partly- and Fully-Dispersed Shock Waves in Gas-Solids Suspensions

As noted previously, the pseudo-shock in the supersonic diffuser of a gas-dynamic injector can be adequately modeled as a single normal shock. The structure of a shock wave in a gas-solids suspension, however, exhibits a number of features [26,27,28] which must be accounted for when analyzing the flow in a gas-dynamic injector.

If the mixture upstream of the shock is in equilibrium, the velocity profile through a standing shock front may be represented, over a wide range of conditions, as shown in Figure 3.2. In such flows, the speed of the mixture upstream of the shock is greater than the frozen speed of sound, that is,

$$U_a > a_f > a_{eq} \quad (3.16)$$

The shock transition of a gas-particle mixture presenting such a

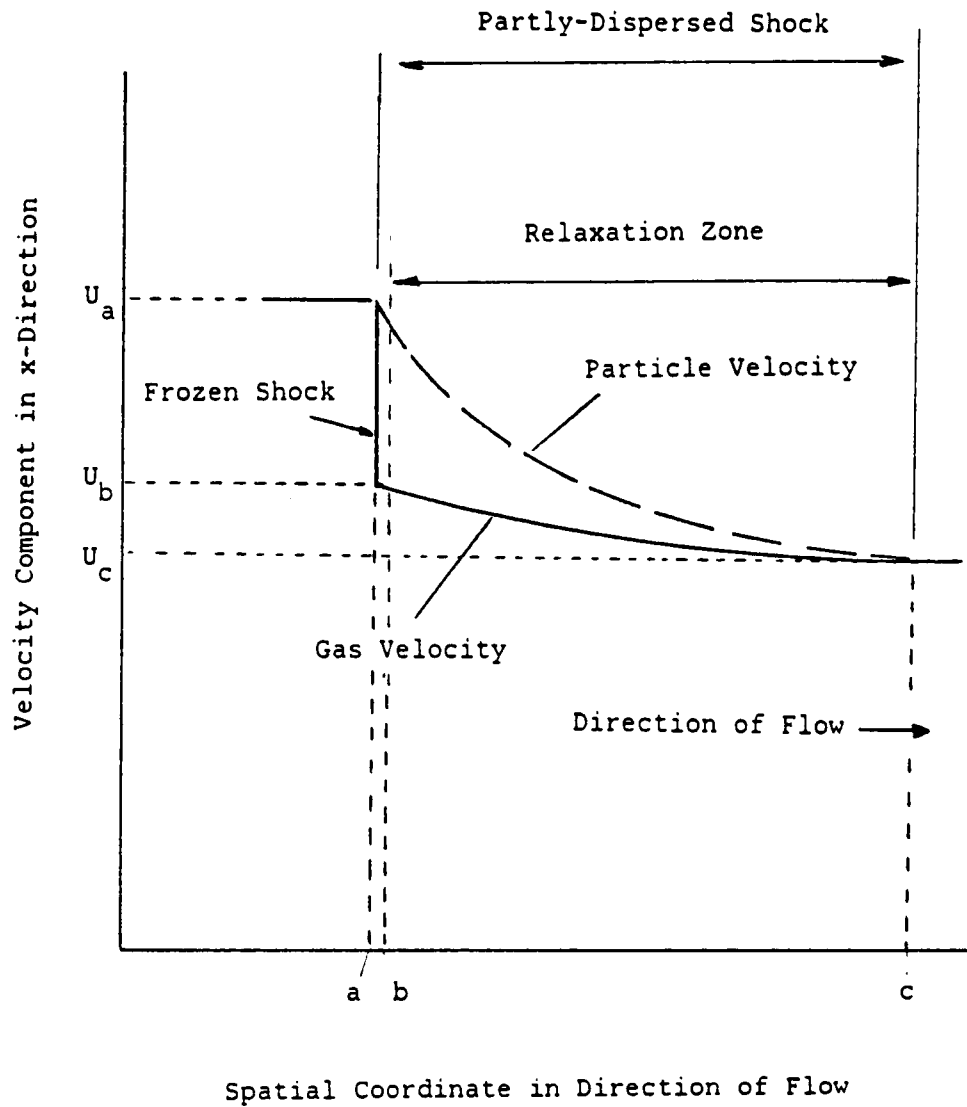


Figure 3.2. The Structure of a Partly-Dispersed Shock Wave in a Gas-Solids Suspension

condition and which has the structure shown in Figure 3.2 is called a "partly-dispersed shock wave".

The velocity across a partly-dispersed shock drops from that of the upstream equilibrium flow (U_a) to that of the downstream equilibrium flow (U_c) in two physically distinct regions. The first region is an ordinary gas shock, or "frozen shock wave", in which only the gas phase experiences changes in both temperature and velocity. The velocity of the gas phase drops from the upstream value U_a , to a value U_b ($>U_c$). Since the thickness of the frozen shock is only a few mean free path lengths, this change in velocity appears as a discontinuity on the scale of the overall length of the shock, as shown in Figure 3.2. The solids particles cannot exchange appreciable amounts of momentum or thermal energy in the extremely short time required to traverse the frozen shock. Thus, both the velocity and the temperature of the particles immediately behind the frozen shock are equal to their respective upstream values. Since the discontinuous shock in the gas phase is not affected by the presence of the particles, all of the gas properties immediately behind the shock may be found with good accuracy from the usual normal shock relations for the clean gas. The second distinct region in a partly-dispersed shock is the "relaxation zone" immediately behind the frozen shock in which the velocities and temperature of the particles and gas equilibrate by momentum exchange and heat transfer.

If the mixture in equilibrium states upstream and downstream of a partly-dispersed shock can be treated as "modified ideal gases", the overall changes in the mixture properties can be predicted with the ordinary normal shock relations for an ideal gas. This model neglects

the finite length of the relaxation zone, which can only be determined by solving the transport equations which portray the details of the equilibration process. This feature of the flow, however, is not of major importance in the present study and, hence, these calculations were not performed.

Next, consider the case where the velocity of the equilibrium mixture upstream of the shock is reduced such that

$$U_a = a_f > a_{eq} . \quad (3.17)$$

The initial disturbance (corresponding to the frozen shock) is now infinitesimally small (a sound wave in the pure gas) which is followed by a disturbance of finite length in the relaxation zone. As U_a continues to decrease the disturbance becomes subsonic in the pure gas, but supersonic in the mixture ($a_f > U_a > a_{eq}$). This flow transition, which is called a "fully-dispersed shock", has no initial disturbance in the gas. The transition between the upstream and downstream equilibrium states takes place continuously across the finite length of the relaxation zone. When U_a decreases until $a_f > U_a = a_{eq}$, the fully-dispersed shock becomes a sound wave in the mixture. Note that pressure disturbances can propagate upstream past either a fully-dispersed shock or a sound wave in the mixture; that is not the case, however, with partly-dispersed shocks. In partly-dispersed shocks no pressure disturbances (sound waves) can move upstream past the frozen shock in the gas.

In the actual operation of the gas-dynamic injector pressure disturbances originated in the high-pressure vessel can propagate upstream into the injector which may result in appreciable changes in the flow conditions. In order to prevent these disturbances from propagating upstream into the device the gas-dynamic injector should operate with a partly-dispersed shock. A criterion for the existence of a partly-dispersed shock is developed next.

Criterion for the Existence of a Partly-Dispersed Shock

Wave in a Gas-Dynamic Injector

Define the Mach numbers, M_{eq} and M_f , for the flow upstream of the shock based on the the equilibrium and frozen sound speeds respectively, as follows:

$$M_{eq} = U/a_{eq} \quad (3.18)$$

and

$$M_f = U/a_f \quad (3.19)$$

Eqs. (3.18) and (3.19) give

$$M_{eq} = (a_f/a_{eq}) M_f \quad (3.20)$$

Substituting eqs. (3.13) and (3.15) in eq. (3.20) gives:

$$M_{eq} = \sqrt{(\gamma/\gamma_s)(R/R_s)} M_f \quad (3.21)$$

For the existence of a partly-dispersed shock, M_f must be greater than unity.

CHAPTER 4

A SIMPLIFIED MATHEMATICAL MODEL OF A GAS-DYNAMIC INJECTOR

Figure 4.1 shows the model that is to be used for the theoretical analysis. The flow field is divided into six distinct regions. Region (A) corresponds to the subsonic acceleration of the primary gas between its stagnation condition and the sonic condition at the throat (section '*'). Region (B) corresponds to the supersonic acceleration of the primary gas between section '*' and section '1' where the injection tube flow begins mixing with the primary flow. Region (C) corresponds to the mixing process carried out at constant pressure between sections '1' and '2'. Region (D) corresponds to the shock compression between sections '2' and '3'. Region (E) corresponds to the subsonic deceleration process between sections '3' and '4'.

The basic problem is to determine the cross sectional areas at each section, that is, to size the device, and to determine the required stagnation pressure of the primary gas (P_{g1}) given the following:

1. the carrier gas properties (R , γ , and c_p);
2. the specific heat of the solid (c);
3. the mass flow rate of solids ($\dot{m}_p$);
4. the primary-gas-to-solids mass flow rate ratio (N_{g1});
5. the secondary-gas-to-solids mass flow rate ratio (N_{g2});
6. the stagnation temperature of the gas-solids suspension in the injection tube (T_{0e});
7. the stagnation temperature of the primary gas (T_{g1});

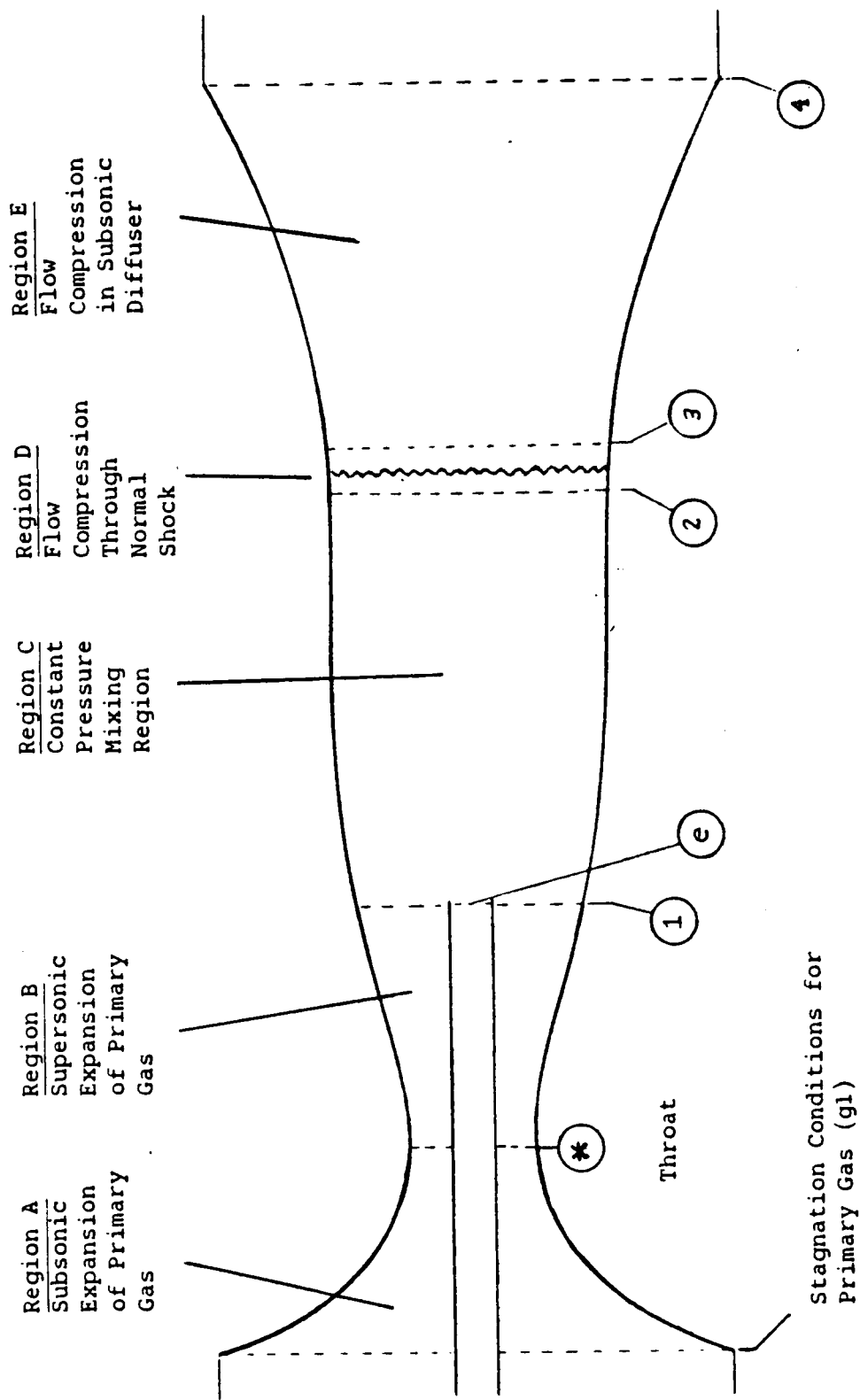


Figure 4.1. Gas-Dynamic Injector Model Used in the Theoretical Analysis

8. the static pressure of the gas-solids suspension in the injection tube exit plane (P_e);
9. the ratio of vessel pressure/injection pressure (P_4/P_e);
10. the Mach number at the injection tube exit (M_e);
11. the Mach number at the inlet of the high-pressure vessel (M_4).

Assumptions Considered in the Theoretical Analysis

1. All flows are steady-state, one-dimensional, and adiabatic.
2. Changes in potential energy are negligible.
3. No work is done on or by the system.
4. Flows are isentropic except during shock compression and mixing.
5. No chemical reactions or phase changes take place.
6. Same carrier gas is used in both streams.
7. The carrier gas is an ideal gas.
8. Properties of gas and solids are constants.
9. The gas-solids suspension is at equilibrium conditions at each cross-section along the device.
10. The solids volume fraction, ϵ , is negligible. Thus, the gas-particle flow is modeled as a flow of an ideal gas with modified properties.
11. The pseudo-shock compression is modeled as a single normal shock compression.
12. The gas-solids relaxation zone behind the shock is negligibly thin compared to the dimensions of the injector. Thus, the

mixture is assumed to achieve equilibrium flow conditions immediately behind the gas shock.

13. The gas-solids flow issuing from the injection tube is subsonic or sonic at the exit section (based on the equilibrium speed of sound).
14. The static pressure in the injection tube at the exit section (P_e) is equal to the pressure in the surrounding supersonic flow (P_1). (P_e is determined by the capability of the low pressure differential solids feeder.)
15. The mixing process of the coflowing jet of gas-solids suspension and the surrounding supersonic gas is carried out at constant pressure.

Derivation of the Governing Equations

Method of Solution

The idea is to relate the conditions between consecutive sections by using the governing equations, namely, the equations for conservation of mass and energy, Newton's second law, and the equation of state. For ideal gases undergoing isentropic processes the conservation equations reduce to the usual isentropic relations and for ideal gases undergoing shock compression processes they reduce to the normal shock relations.

The continuity equation

$$\dot{m}_x = \rho_x U_x A_x \quad (4.1)$$

is applied at each section in order to relate cross-sectional areas and

mass flow rates. The isentropic equations

$$\frac{P_{0x}}{P_x} = \left[1 + \frac{(\gamma_s - 1)}{2} M_x^2 \right]^{\gamma_s / (\gamma_s - 1)} \quad (4.2)$$

and

$$\frac{T_{0x}}{T_x} = 1 + \frac{(\gamma_s - 1)}{2} M_x^2 \quad (4.3)$$

are applied at each section in order to relate static and stagnation conditions at that particular section. Stagnation conditions in sections separated by regions where the flow is isentropic maintain the same value; that is,

$$P_{0y} = P_{0x} \quad (4.4)$$

and

$$T_{0y} = T_{0x} \quad (4.5)$$

where "x" and "y" represent two such locations. The normal shock relations are used to relate conditions at sections '2' and '3'.

Expressions For Mass Flow Rates

The parameters N_{g1} and N_{g2} are defined as

$$N_{g1} = \dot{m}_{g1} / \dot{m}_p \quad (4.6)$$

and

$$N_{g2} = \dot{m}_{g2} / \dot{m}_p \quad (4.7)$$

Note that the mass flow rates of primary and secondary gases, $\dot{m}_{g1}$ and $\dot{m}_{g2}$, are dependent variables which are determined by the following relationships

$$\dot{m}_{g1} = \dot{m}_p N_{g1} \quad (4.8)$$

and

$$\dot{m}_{g2} = \dot{m}_p N_{g2} \quad (4.9)$$

The mass flow rate at section 'e' is given by

$$\dot{m}_e = \dot{m}_p + \dot{m}_{g2} \quad (4.10)$$

or in terms of the given mass parameters,

$$\dot{m}_e = \dot{m}_p (1 + N_{g2}) \quad (4.11)$$

The mass flow rates at sections '2', '3', and '4' have the same value which is defined as the total mass flow rate, $\dot{m}_t$, given by:

$$\dot{m}_t = \dot{m}_p + \dot{m}_{g2} + \dot{m}_{g1} \quad (4.12)$$

In terms of the given parameters, this equation can be rewritten as

$$\dot{m}_t = \dot{m}_p (1 + N_{g1} + N_{g2}) \quad (4.13)$$

Flow Properties

Since the equilibrium flow condition applies at sections 'e', '2', '3', and '4', the mixture at these sections is treated as an ideal gas with modified properties. The properties of the gas-solid suspension at

these sections can be computed by using eqs. (3.6), (3.10), and (3.12):

$$R_s = \frac{R}{(1+\eta)} , \quad (3.6)$$

$$\gamma_s = \gamma \frac{(1+\gamma(c/c_p))}{(1+\gamma\eta(c/c_p))} , \quad (3.10)$$

and

$$c_{ps} = c_p \frac{(1+(c/c_p))}{(1+\eta)} . \quad (3.12)$$

where:

R = ideal gas constant for the carrier gas,

γ = gas specific heat ratio for the carrier gas,

c/c_p = ratio of specific heat of the solid to the constant pressure specific heat of the gas, and

η = the solids loading ratio.

At the injection tube exit section the solids loading ratio is given by

$$\eta = \frac{\dot{m}_p}{\dot{m}_{g2}} = \frac{1}{N_{g2}} . \quad (4.14)$$

Substituting this result in eqs. (3.6), (3.10), and (3.12), yields

$$R_e = R \frac{N_{g2}}{(N_{g2}+1)} , \quad (4.15)$$

$$\gamma_e = \gamma \frac{(N_{g2} + (c/c_p))}{(N_{g2} + \gamma(c/c_p))} , \quad (4.16)$$

and

$$c_{pe} = c_p \frac{(N_{g2} + (c/c_p))}{(N_{g2} + 1)} \quad (4.17)$$

At sections '2', '3', and '4', the solids loading ratio has the same value which is given by

$$\eta = \frac{\dot{m}_p}{(\dot{m}_{g1} + \dot{m}_{g2})} = \frac{1}{(N_{g1} + N_{g2})} \quad (4.18)$$

This result is substituted into eqs. (3.6), (3.10), and (3.12) to obtain the properties of the mixture at those sections:

$$R_m = R \frac{(N_{g1} + N_{g2})}{(N_{g1} + N_{g2} + 1)} \quad (4.19)$$

$$\gamma_m = \gamma \frac{(N_{g1} + N_{g2} + (c/c_p))}{(N_{g1} + N_{g2} + \gamma(c/c_p))} \quad (4.20)$$

and

$$c_{pm} = c_p \frac{(N_{g1} + N_{g2} + (c/c_p))}{(N_{g1} + N_{g2} + 1)} \quad (4.21)$$

For fixed N_{g1} and N_{g2} the properties R_m , γ_m , c_{pm} , R_e , γ_e , and c_{pe} have fixed values. Thus, in the remainder of the analysis, these quantities are considered as known constants.

Subsonic Expansion Process of Primary Gas

Since the expansion process through region (A) is an isentropic process, the stagnation conditions at the throat are the same as for the gas in the stagnation chamber, that is,

$$P_0^* = P_{g1} \quad (4.22)$$

and

$$T_0^* = T_{g1} \quad (4.23)$$

Conditions at Section '*'

At this section the flow is at sonic conditions ($M^* = 1$).
According to the continuity equation

$$\dot{m}_{g1} = \rho^* U^* A^* \quad (4.24)$$

$$\text{where } \rho^* = \frac{P^*}{R T^*} \quad (4.25)$$

$$\text{and } U^* = \sqrt{\gamma R T^*} \quad (4.26)$$

Substituting these expressions in eq. (4.24):

$$\dot{m}_p N_{g1} = P^* A^* \sqrt{\frac{\gamma}{R T^*}} \quad (4.27)$$

By the use of isentropic relations the static pressure and temperature are related to their stagnation values as follows:

$$\frac{P_0^*}{P^*} = \left[\frac{(\gamma+1)}{2} \right]^{\gamma/(\gamma-1)} \quad (4.28)$$

and

$$\frac{T_0^*}{T^*} = \frac{(\gamma+1)}{2} \quad (4.29)$$

Supersonic Expansion of Primary Gas Between Sections '*' and '1'

The supersonic expansion through region (B) is an isentropic process; thus,

$$P_{01} = P_0^* \quad (4.30)$$

and

$$T_{01} = T_0^* \quad (4.31)$$

Conditions at Section '1'

The continuity equation states that

$$\dot{m}_{g1} = \rho_1 U_1 A_1 \quad (4.32)$$

$$\text{where } \rho_1 = \frac{P_1}{R T_1} \quad (4.33)$$

$$\text{and } U_1 = M_1 \sqrt{\gamma R T_1} \quad (4.34)$$

Substituting eq. (4.8) in eq. (4.32):

$$\dot{m}_p N_{g1} = P_1 A_1 M_1 \sqrt{\frac{\gamma}{R T_1}} \quad (4.35)$$

By the use of isentropic relations, the static pressure and temperature at section '1' are related to their stagnation values by:

$$\frac{P_{01}}{P_1} = \left[1 + \frac{(\gamma-1)}{2} M_1^2 \right]^{\gamma/(\gamma-1)} \quad (4.36)$$

and

$$\frac{T_{01}}{T_1} = 1 + \frac{(\gamma-1)}{2} M_1^2 \quad (4.37)$$

Conditions at Section 'e'

The continuity equation states that

$$\dot{m}_e = \rho_e U_e A_e \quad (4.38)$$

$$\text{where } \rho_e = \frac{P_e}{R_e T_e} \quad (4.39)$$

$$\text{and } U_e = M_e \sqrt{\gamma_e R_e T_e} \quad (4.40)$$

Substituting eq. (4.11) in eq. (4.38) gives:

$$\dot{m}_p (1+N_{g2}) = P_e A_e M_e \sqrt{\frac{\gamma_e}{R_e T_e}} \quad (4.41)$$

By the use of isentropic relations the static temperature and pressure are related to their stagnation values at section 'e'. This gives:

$$\frac{P_{0e}}{P_e} = \left[1 + \frac{(\gamma_e-1)}{2} M_e^2 \right]^{\gamma_e/(\gamma_e-1)} \quad (4.42)$$

and

$$\frac{T_{0e}}{T_e} = 1 + \frac{(\gamma_e - 1) M_e^2}{2} . \quad (4.43)$$

Since the assumption was made that the equilibrium Mach number of the flow in the injection tube is less than or equal to one, it follows that

$$P_1 = P_e . \quad (4.44)$$

Constant Pressure Mixing Process Between Sections '1' and '2'

The only condition specified for this process is that the static pressure remains constant throughout the region. Thus,

$$P_2 = P_e . \quad (4.45)$$

Since the process in region (C) is a non-isentropic mixing process of two different fluids with different stagnation pressures and temperatures, it is necessary to apply the conservation equations in order to relate the flow parameters at sections '1' and '2'. Figure 4.2 shows the control volume used for the analysis.

The continuity equation simply states that

$$\dot{m}_{g1} + \dot{m}_e = \dot{m}_t = \rho_2 U_2 A_2 \quad (4.46)$$

$$\text{where } \rho_2 = \frac{P_2}{R_m T_2} \quad (4.47)$$

$$\text{and } U_2 = M_2 \sqrt{\gamma_m R_m T_2} . \quad (4.48)$$

Substituting eq. (4.13) and these expressions in (4.46) gives:

$$\dot{m}_p (1 + N_{g2} + N_{g1}) = P_2 A_2 M_2 \sqrt{\frac{\gamma_m}{R_m T_2}} . \quad (4.49)$$

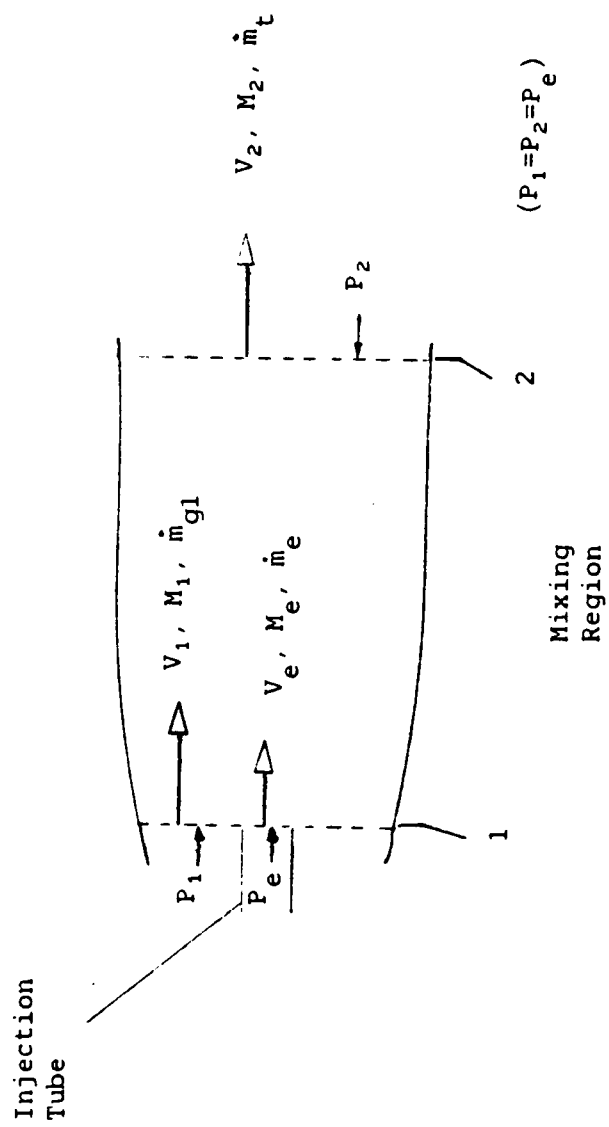


Figure 4.2. Control Volume for the Mixing Region

For steady state flow the x-component of Newton's second law reduces to

$$\sum F_x = \int_{c.s.} \rho U_x (\vec{U} \cdot \vec{n}) dA \quad . \quad (4.50)$$

The pressure throughout the mixing region is constant. Therefore, $\sum F_x = 0$. The right hand side of eq. (4.50) is the rate of change of momentum given by

$$\begin{aligned} \int_{c.s.} \rho U_x (\vec{U} \cdot \vec{n}) dA &= \rho_1 U_1 (-U_1 A_1) + \\ &+ \rho_e U_e (-U_e A_e) + \\ &+ \rho_2 U_2 (U_2 A_2) \quad . \end{aligned} \quad (4.51)$$

Substituting eq. (4.51) in eq. (4.50) gives

$$0 = \rho_1 U_1 (-U_1 A_1) + \rho_e U_e (-U_e A_e) + \rho_2 U_2 (U_2 A_2) \quad (4.52)$$

which can be rewritten as

$$\begin{aligned} N_{g1} M_1 \sqrt{\gamma R T_1} + (1+N_{g2}) M_e \sqrt{\gamma_e R_e T_e} &= \\ = (1+N_{g1}+N_{g2}) M_2 \sqrt{\gamma_m R_m T_2} \quad . \end{aligned} \quad (4.53)$$

The equation for conservation of energy for steady state flow with constant properties reduces to the form

$$\dot{m}_{g1} h_{01} + \dot{m}_e h_{0e} = \dot{m}_t h_{02} \quad (4.54)$$

or, for an ideal gas,

$$\dot{m}_{g1} c_p T_{01} + \dot{m}_e c_{pe} T_{0e} = \dot{m}_t c_{pm} T_{02} \quad (4.55)$$

Substituting the expressions for mass flow rates into this equation gives

$$c_p T_{01} N_{g1} + c_{pe} T_{0e} (1+N_{g2}) = c_{pm} T_{02} (1+N_{g1}+N_{g2}) \quad (4.56)$$

The isentropic relations which relate static and stagnation conditions for pressure and temperature at section '2' are:

$$\frac{P_{02}}{P_2} = \left[1 + \frac{(\gamma_m - 1)}{2} M_2^2 \right]^{\gamma_m / (\gamma_m - 1)} \quad (4.57)$$

and

$$\frac{T_{02}}{T_2} = 1 + \frac{(\gamma_m - 1)}{2} M_2^2 \quad (4.58)$$

Shock Compression Process: sections '2'-'3'

In region (D) the normal shock equations are applied to relate conditions at sections '2' and '3'. The following equations are valid for the shock transition:

$$\frac{P_3}{P_2} = \frac{(1 + \gamma_m M_2^2)}{(1 + \gamma_m M_3^2)} \quad (4.59)$$

$$T_{03} = T_{02} \quad (4.60)$$

and

$$M_3^2 = \frac{M_2^2 + \frac{2}{(\gamma_m - 1)}}{\frac{2 \gamma_m M_2^2}{(\gamma_m - 1)} - 1} \quad (4.61)$$

The following isentropic relations apply at section '3'

$$\frac{P_{03}}{P_3} = \left[1 + \frac{(\gamma_m - 1) M_3^2}{2} \right]^{\gamma_m / (\gamma_m - 1)} \quad (4.62)$$

and

$$\frac{T_{03}}{T_3} = 1 + \frac{(\gamma_m - 1) M_3^2}{2} \quad (4.63)$$

Subsonic Compression Process: Sections '3'-'4'

The flow between sections '3' and '4' is isentropic. Thus, the stagnation values for pressure and temperature are unchanged between these sections, that is,

$$P_{04} = P_{03} \quad (4.64)$$

and

$$T_{04} = T_{03} \quad (4.65)$$

Conditions at Section '4'

The continuity equation states that

$$\dot{m}_t = \rho_4 U_4 A_4 \quad (4.66)$$

$$\text{where } \rho_4 = \frac{P_4}{R_m T_4} \quad (4.67)$$

$$\text{and } U_4 = M_4 \sqrt{\gamma_m R_m T_4} \quad (4.68)$$

Substituting these expressions and eq. (4.13) in eq. (4.66) yields:

$$\dot{m}_p (1+N_{g1}+N_{g2}) = P_4 A_4 M_4 \sqrt{\frac{\gamma_m}{R_m T_4}} \quad (4.69)$$

By the use of isentropic relations, the static temperature and pressure are related to their stagnation values at section '4' by:

$$\frac{P_{04}}{P_4} = \left[1 + \frac{(\gamma_m - 1)}{2} M_4^2 \right]^{\gamma_m / (\gamma_m - 1)} \quad (4.70)$$

and

$$\frac{T_{04}}{T_4} = 1 + \frac{(\gamma_m - 1)}{2} M_4^2 \quad (4.71)$$

Summary of the Analytical Model

Tables 4.1 and 4.2 list the set of governing equations and the unknowns. There are 37 unknowns in 37 equations so that the solution is possible. A program was written in FORTRAN IV to solve this set of equations. A listing of this program is given in Appendix A and the flow diagram for the program is in Appendix B.

Table 4.1. List of Independent Equations in the Analytical Model

Equation		Equation	
1	(4.15)	20	(4.43)
2	(4.16)	21	(4.44)
3	(4.17)	22	(4.45)
4	(4.18)	23	(4.49)
5	(4.19)	24	(4.53)
6	(4.20)	25	(4.56)
7	(4.21)	26	(4.57)
8	(4.22)	27	(4.58)
9	(4.23)	28	(4.59)
10	(4.27)	29	(4.60)
11	(4.28)	30	(4.61)
12	(4.29)	31	(4.62)
13	(4.30)	32	(4.63)
14	(4.31)	33	(4.64)
15	(4.35)	34	(4.65)
16	(4.36)	35	(4.69)
17	(4.37)	36	(4.70)
18	(4.41)	37	(4.71)
19	(4.42)		

Table 4.2. List of Unknowns

Unknown		Unknown	
1	R_e	20	T_e
2	γ_e	21	A_e
3	c_{pe}/c_p	22	M_e
4	R_m	23	P_{02}
5	γ_m	24	P_2
6	c_{pm}/c_p	25	T_{02}
7	P_{gl}	26	T_2
8	P_0^*	27	A_2
9	P^*	28	M_2
10	T_0^*	29	P_{03}
11	T^*	30	P_3
12	A^*	31	T_{03}
13	P_{01}	32	T_3
14	P_1	33	M_3
15	T_{01}	34	P_{04}
16	T_1	35	T_{04}
17	A_1	36	T_4
18	M_1	37	A_4
19	P_{0e}		

Minimum Possible Value of the Exit/Injection Pressure
Ratio Which Allows the Existence of a Partly-Disperse
Shock in the Gas-Dynamic Injector

It is necessary to check whether the pressure ratio P_4/P_e is high enough to allow the formation of a partly-dispersed shock in region (D). A partly-dispersed shock can exist only if the Mach number based on frozen conditions (M_f) is greater than unity. The minimum value of the Mach number based on equilibrium conditions which allows the existence of a partly-dispersed shock is given by eq. (3.21) when setting M_f to 1. Rewriting eq. (3.21) in terms of the appropriate parameters involved in this analysis gives the minimum value of M_2 required for the existence of a partly-dispersed shock:

$$M_{2(\min)} = \sqrt{\frac{\gamma R}{\gamma_m R_m}} \quad (4.72)$$

Thus, $M_{2(\min)}$ can be determined once the flow properties γ_m and R_m are known. An expression for P_4/P_e can be written in terms of the product

$$\left[\frac{P_4}{P_e} \right] = \left[\frac{P_4}{P_{04}} \right] \left[\frac{P_{04}}{P_{03}} \right] \left[\frac{P_{03}}{P_3} \right] \left[\frac{P_3}{P_2} \right] \left[\frac{P_2}{P_e} \right] \quad (4.73)$$

Replacing eqs. (4.70), (4.64), (4.62), (4.59), and (4.45) in the above equation and substituting $(M_3)^2$ by the right-hand side of eq. (4.61) gives P_4/P_e as a function of M_2 , M_4 , and γ_m :

$$\frac{P_4}{P_e} = \left[\frac{\frac{(\gamma_m + 1) M_2^2}{2}}{1 + \frac{(\gamma_m - 1) M_4^2}{2}} \right]^{\frac{\gamma_m}{(\gamma_m - 1)}} \left[\frac{2 \gamma_m M_2^2}{(\gamma_m + 1)} - \frac{(\gamma_m - 1)}{(\gamma_m + 1)} \right]^{1/(1 - \gamma_m)} \quad (4.74)$$

Substitution of M_2 by $M_{2(\min)}$ in eq. (4.74) results in an expression that gives the minimum possible value of the ratio P_4/P_e ($[P_4/P_e]_{(\min)}$) which allows the formation of a partly-dispersed shock. Thus, if the design value of the pressure ratio P_4/P_e is less than $[P_4/P_e]_{(\min)}$, the program execution is halted and a message is displayed.

Maximum Possible Value of the Exit/Injection Pressure

Ratio for Which the Flow Can Be Established

in the Gas-Dynamic Injector

There is a limit on the maximum velocity for the primary gas in the supersonic region at section '1' (end of supersonic expansion) which occurs when the flow has the theoretically minimum possible static temperature. These conditions exist when the Mach number at that section (M_1) approaches the value of infinity. Since the static pressure at section '1' is equal to P_e (which is specified), the stagnation pressure for primary gas (P_{01}) has to approach infinity such that eq. (4.36) is satisfied. Using eq. (4.37) and knowing that $U_1 = M_1 \sqrt{\gamma R T_1}$ it can be shown that

$$U_1 = \sqrt{\frac{2 \gamma R (T_{01} - T_1)}{(\gamma - 1)}} \quad (4.75)$$

where U_1 is the velocity at section '1'. For the theoretically minimum

possible value of the static temperature at that section ($T_1=0$), this equation becomes

$$U_{1(max)} = \sqrt{\frac{2 \gamma R T_{01}}{(\gamma - 1)}} \quad (4.76)$$

where $U_{1(max)}$ is the maximum velocity at section '1'. For a given value of the primary gas mass flow rate, $\dot{m}_{g1}$, the limit of maximum velocity imposes a limit on the amount of momentum transfer that can occur between the primary gas and the the gas-solids suspension exiting the injection tube. Consequently, assuming that all conditions are fixed except for the cross-sectional areas and stagnation pressure of primary gas, there will be a limit on the maximum value of the pressure ratio, P_4/P_e , the gas-dynamic injector is capable of handling. This limit arises because not enough momentum can be transferred from the primary gas to the gas-solids suspension in order to accelerate it to a high enough speed so that after compression, the whole mixture reaches the desired pressure. An expression for the maximum possible value of the Mach number at section '2' ($M_{2(max)}$) is obtained by substituting M_1 from eq. (4.37), T_e from eq. (4.43), and T_2 from eq. (4.58) into eq. (4.53), which gives:

$$M_{2(max)} = \left[\frac{\gamma_m R_m T_{02} (N_{g1} + N_{g2} + 1)^2 (\gamma_m - 1)}{\left[N_{g1} \sqrt{\frac{2 \gamma R T_{01}}{(\gamma - 1)}} + (1 + N_{g2}) \sqrt{\frac{\gamma_e R_e T_{0e}}{1 + \frac{(\gamma_e - 1)}{M_e^2}}} \right]^2 - \frac{(\gamma_m - 1)}{2}} \right]^{-.5} \quad (4.77)$$

All the parameters in eq. (4.77) are known with the exception of T_{02} . However, T_{02} can be determined using eq. (2.56). Note that the total temperature at section '1', T_{01} , is equal to the total temperature in the stagnation chamber (T_{g1}) of the primary gas. Once $M_{2(\max)}$ is known, the maximum pressure ratio $[P_4/P_e]_{(\max)}$ is computed using eq. (4.74). If P_4/P_e (which is given as a known parameter) is greater than $(P_4/P_{e(\max)})$, then the computer program halts execution. Otherwise, the program continues with the solution of the set of equations. The program performs a half interval search iteration to compute the value of M_2 (which can not be determined analytically) using eq. (4.74). The value of M_2 is used as the independent variable and $[P_4/P_e]_{(\text{iteration})}$ is relaxed to the actual value P_4/P_e (which is known). Once M_2 is known, M_1 may be computed by combining eqs. (4.37) and (4.53) to yield

$$M_1 = \left[\frac{1}{\phi} - \frac{(\gamma-1)}{2} \right]^{-.5} \quad (4.78)$$

where

$$\phi = \frac{[(1+N_{g1}+N_{g2}) M_2 \sqrt{\gamma_m R_m T_2} - (1+N_{g2}) M_e \sqrt{\gamma_e R_e T_e}]^2}{\gamma R T_{01} (N_{g1})^2} \quad (4.79)$$

Note that T_2 is determined once M_2 is known. T_e can be determined directly from eq. (4.43).

CHAPTER 5

A PARAMETRIC STUDY OF THE GAS-DYNAMIC INJECTOR FOR A TYPICAL APPLICATION

In general, an analytical model of an engineering system may be used to perform either a "sizing (design) study" or a "performance study" of that system. In a sizing study, the performance of the system is specified and the model is used to determine the dimensions of the system and, perhaps, one or more operational parameters required to obtain the specified performance. In a performance study, the system itself is completely specified and its performance is determined as a function of the operating variables. The parametric study presented in this chapter is a sizing study of a gas-dynamic injector for a typical application: the feeding of powdered coal to a combustor which operates at an elevated pressure.

Figure 5.1 shows a process of pressurized coal combustion where power is directly generated by expanding the products of high-pressure air/coal combustion through a gas turbine. The process carried out inside the combustor is known as pressurized fluidized-bed combustion (PFBC). The powdered coal gravitates against the rising stream of hot gases resulting from the combustion process to form a well-defined upper horizontal surface. The dimensions of the coal particles are between .1 mm and 5. mm [5,6,18].

High-pressure coal combustion is also used in magnetohydrodynamic (MHD) power generation. Here, the products of combustion are ionized and accelerated to high speeds through a nozzle and then passed through

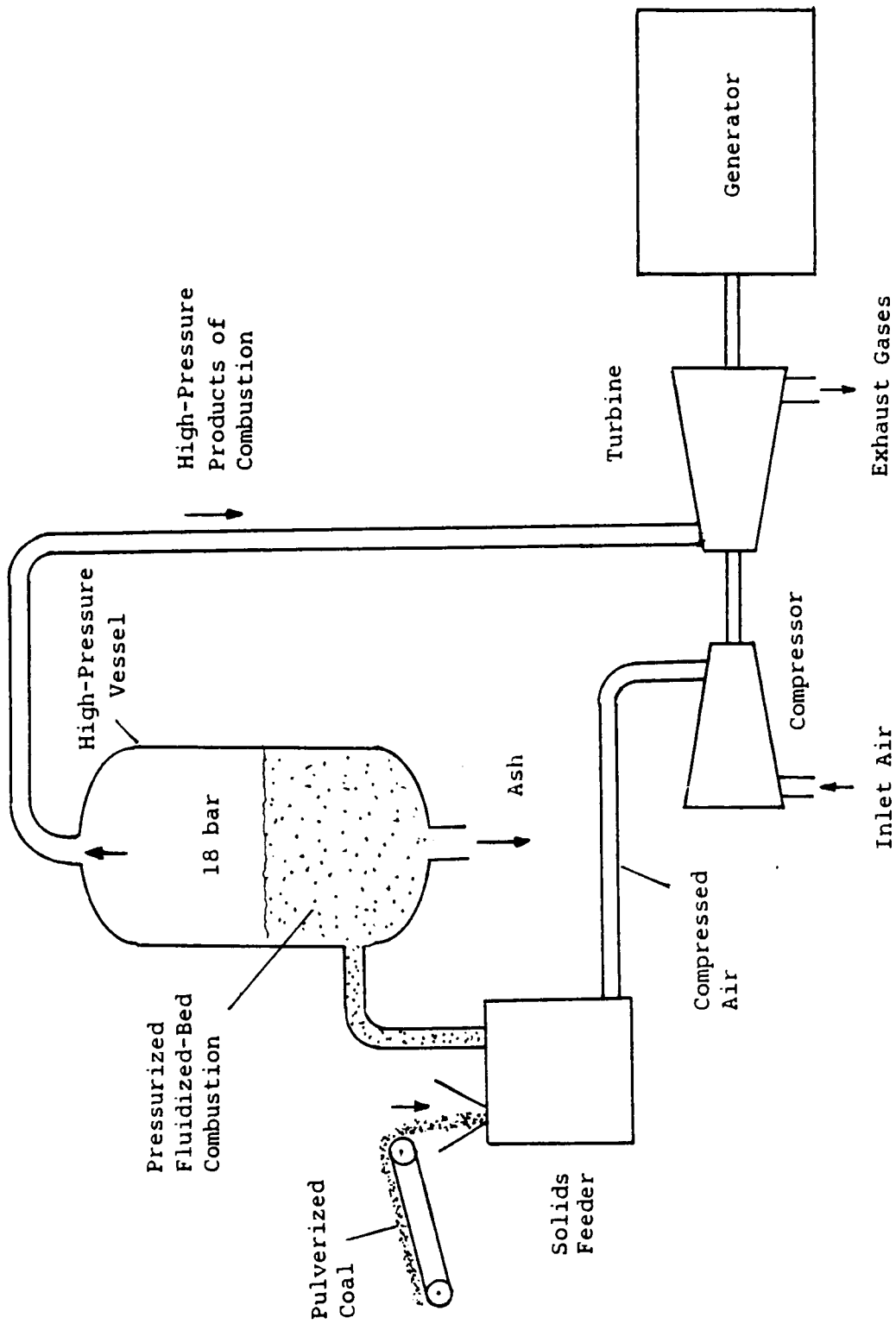


Figure 5.1. Schematic Representation of the Process of Pressurized Coal Combustion Applied to Power Generation

a magnetic field so that an electric current is induced in electrodes placed at the channel walls. Typical pressures in MHD combustors are on the order of 8 bar [7].

This study, which was conducted to examine the feasibility of the gas-dynamic injector for a specific application, determines the effects of varying the nondimensional mass flow parameters N_{g1} and N_{g2} on the injection tube area, A_e , the area ratios A^*/A_e , A_1/A_e , A_2/A_e , and A_4/A_e , and the overall pressure ratio P_{g1}/P_4 . In addition, a study is conducted to observe the effects of the static pressure and total temperature at the injection tube exit, P_e and T_{0e} , on the overall pressure ratio, P_{g1}/P_4 . The results were obtained using the computer program GDI which is listed in Appendix A.

Values of the Design Variables for the Parametric Study

In this study the gas is assumed to be air and the solid coal. The exit pressure of the gas-dynamic injector is fixed at 18 bar (upper limit for pressurized coal combustion [5,6,18]). The mass flow rate of the solids was fixed at 1 Kg/s. (Since all the cross-sectional areas are proportional to the solids mass flow rate, the geometry of the GDI can be easily determined for any other value of the solids mass flow rate.) The total temperature of the primary air is fixed at 700°K which is below the ignition temperature of coal (approximately 780°K [23]) by a reasonable safety margin. In order to study the effects of the parameters N_{g1} and N_{g2} on the cross-sectional areas and on the pressure ratio P_{g1}/P_4 , the static pressure at the injection tube exit (P_e) is fixed at 1 bar and the total temperature (T_{0e}) is fixed at the same

value of that of the primary air, 700°K. The data used in this study is shown in Table 5.1. The numerical results are in Appendix C (Tables C.1 to C.8). These results are presented as functions of the parameters N_{g1} and N_{g2} with N_{g1} varying from 0 to 180 and N_{g2} varying from 0.2 to 1.0. Additional cases were studied having N_{g2} fixed at 1. and P_e varying from 1 bar to 4 bar with all other parameters unchanged in order to observe the effects of P_e on P_{g1}/P_4 . Finally, the effects of the variation of T_{0e}/T_{g1} on P_{g1}/P_e is studied. As before, N_{g2} was fixed at 1.0. P_e was fixed at 1 bar as a reference. Two values of T_{0e} were used for comparison; they are 700°K and 300°K which give $T_{0e}/T_{g1} = 1$ and $T_{0e}/T_{g1} = .429$ respectively. ($T_{0e} = 300^\circ\text{K}$ is a lower limit approximately equal to the atmospheric temperature). The results of the effects of P_e and T_{0e}/T_{g1} on the parameter P_{g1}/P_4 are presented in Tables C.9 and C.10.

Discussion of Results

Figure 5.2 shows plots of the pressure ratio P_{g1}/P_4 as a function of N_{g1} and N_{g2} . The pressure ratio P_{g1}/P_4 decreases with increasing N_{g1} . In other words, a lower pressure in the stagnation chamber (P_{g1}) is required as N_{g1} is increased for a fixed value of N_{g2} . (When N_{g1} is increased, a larger amount of momentum is available to accelerate the gas-solids suspension issuing from the injection tube and, consequently, a smaller total pressure, P_{g1} , is needed.) The opposite effect is observed when increasing N_{g2} for a fixed value of N_{g1} . An increase in secondary air mass flow rate signifies an increase in the total low-speed mass of gas-solids suspension to be accelerated. Therefore, a

Table 5.1. Data Used in the Parametric Study

Ratio of Specific Heats of Air	$\gamma = 1.4$
Gas Constant of Air	$R = 287. \text{ N-m/Kg-K}$
Ratio of Specific Heat of Coal to Constant-Pressure Specific Heat of Air	$c/c_p = 1.25$
Density of Coal	$d = 1360. \text{ Kg/m}^3$
Mass Flow Rate of Particles (Coal)	$\dot{m}_p = 1. \text{ Kg/s}$
Ratio of Total Temperature of the Gas-Solids Suspension Entering the GDI to the Total Temperature of the Primary Gas	$T_{0e}/T_{gl} = 1$
Total Temperature of the Primary Gas	$T_{gl} = 700.^{\circ}\text{K}$
Inlet Pressure of Gas-Solids Suspension	$P_e = 1. \text{ bar}$
Inlet Pressure of High-Pressure Vessel	$P_4 = 18. \text{ bar}$
Mach Number at Injection Tube Exit Section	$M_e = 1.$
Mach Number at Inlet of High-Pressure vessel	$M_4 = .1$

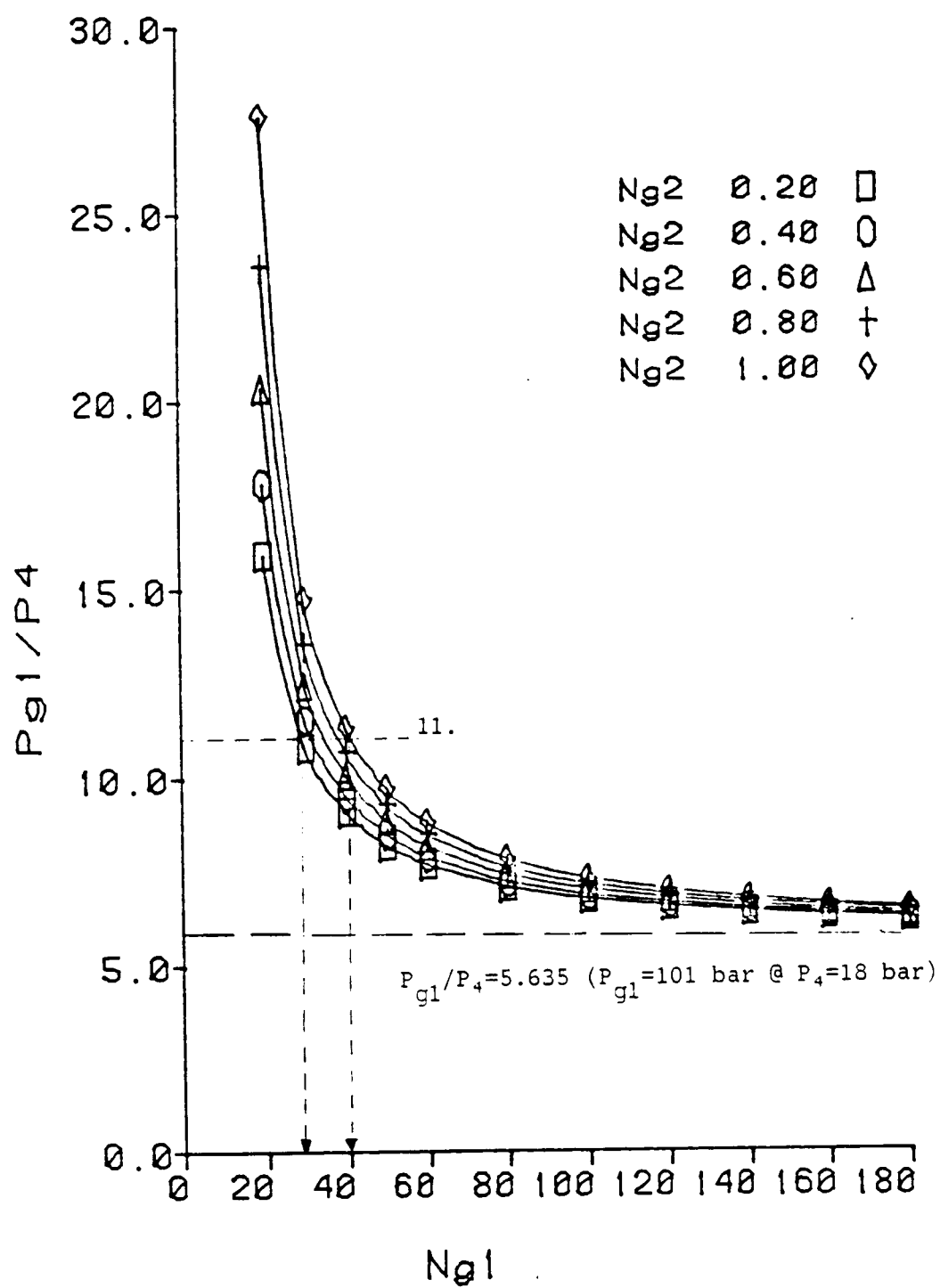


Figure 5.2. P_{g1}/P_4 as a Function of N_{g1} and N_{g2}

larger amount of momentum to be provided by the primary gas and either a higher total pressure or an increase in mass flow rate of primary gas is needed. As N_{g1} approaches infinity, P_{g1}/P_4 approaches a finite value of 5.635. This value of P_4/P_e corresponds to the limit when primary air alone is flowing through the injector. In this limiting case the GDI operates with the minimum possible stagnation pressure of the primary air which is 101 bar (approx.). A practical upper limit of P_{g1} is around 200 bar. Thus, for the case being studied where $P_4=18$ bar, the practical upper limit of P_{g1}/P_4 is about 11. A practical lower limit on N_{g1} can be estimated using Figure 5.2. A horizontal line at $P_{g1}/P_4=11$ which intercept the family of curves defined by N_{g2} determines a range for possible minimum limits on N_{g1} . The minimum practical limit for N_{g1} varies from 30 to 40 as N_{g2} varies from .2 to 1.

Note that N_{g2} should be as small as possible so that the pressure and mass flow rate requirements (power) of primary gas be not so severe. In this study N_{g2} was not given values below .2 because of limits imposed on the solids volume fraction, ϵ , (Chapter 3). For $N_{g2} = .2$ the volume fraction of the gas-solids suspension in the injection tube is $\epsilon=.0019$. while the recommended upper limit is $\epsilon=.001$ for the equilibrium limit to apply. The volume fraction for the cases where $N_{g2}=4$ and above are, however, less than .001. Thus, the practical lower limit for N_{g2} must be close to .2 for this particular case.

Figure 5.3 shows plots of the ratio $[P_4/P_e]_{(max)}$ as a function of N_{g1} . Each of these plots represents the maximum value of P_4/P_e that can be attained given specific values of N_{g1} and N_{g2} . From another point of view, these plots determine the minimum value of N_{g1} below which it is

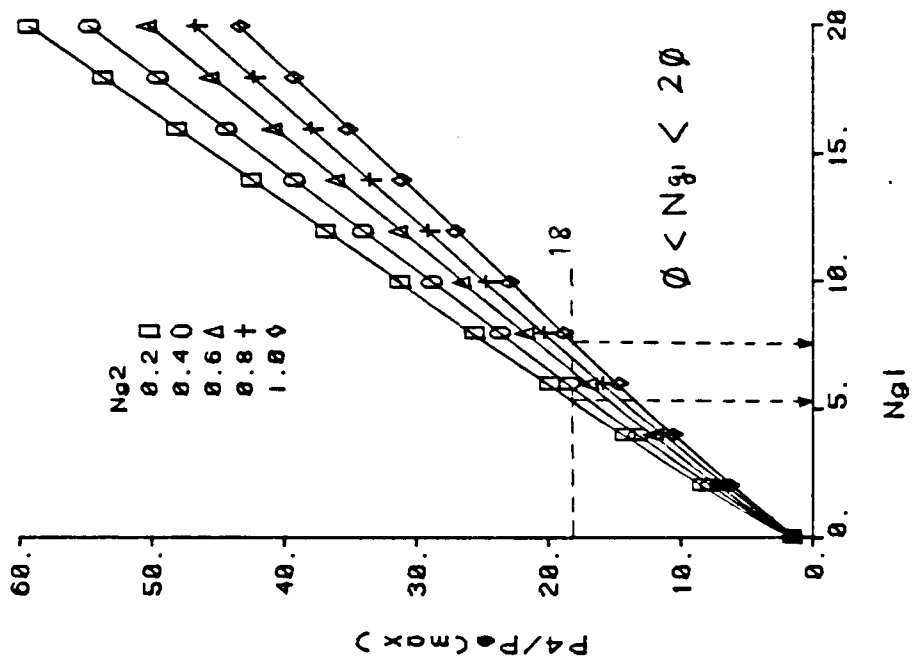
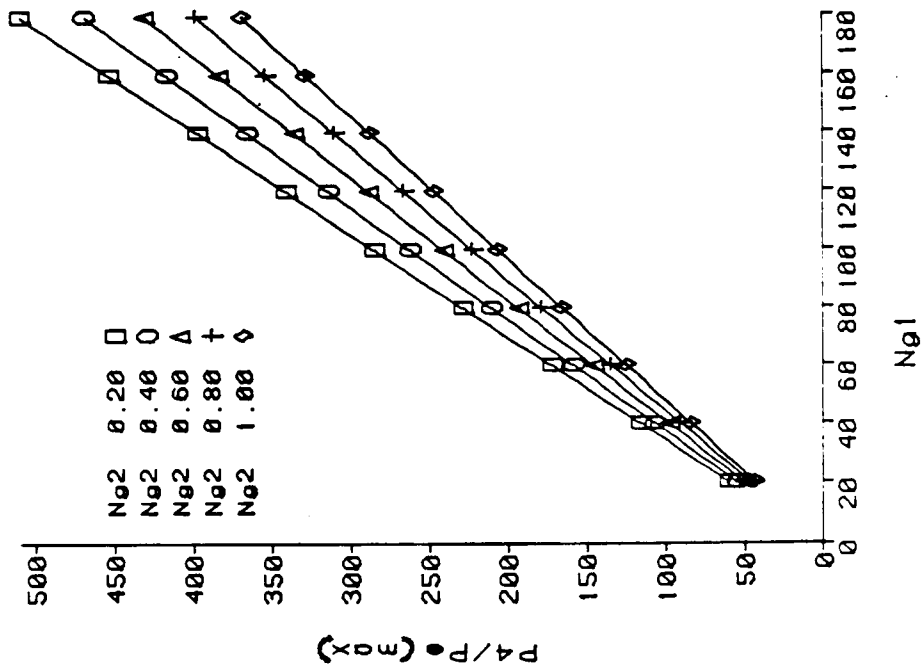


Figure 5.3. Maximum Possible Value of P_4/P_e as a Function of Ng_1 and Ng_2

impossible for the flow to occur when values of P_4/P_e and N_{g2} are specified. Since $P_4/P_e = 18$, a range for the minimum theoretical value of N_{g1} from 5 to 7.5 is obtained as N_{g2} varies from .2 to 1.0. Note that these theoretical minimum values of N_{g1} lie below the practical lower limits of the same parameter (30 to 40 as mentioned above). $[P_4/P_e]_{(max)}$ appears to be a linear function of N_{g1} , but it is actually a complicated, nonlinear function of N_{g1} which approaches straight-line behaviour as N_{g1} is increased (see Appendix D). $[P_4/P_e]_{(max)}$ is not a function of P_e , therefore, these plots may be used to estimate $P_4(max)$ given any value of P_e for $M_4 = 0.1$ and $M_e = 1.0$. It is interesting to note that when $T_{g1}/T_{0e} = 1$, $[P_4/P_e]_{(max)}$ does not depend on the value of T_{g1} (or T_{0e}). Therefore, $[P_4/P_e]_{(max)}$ becomes only a function of the parameters M_e , M_4 , N_{g1} , and N_{g2} .

Figure 5.4 shows the effect produced by the variation of N_{g1} and N_{g2} on the minimum possible value of P_4/P_e such that a discontinuous shock front is formed in the injector. Only two values of N_{g2} were used (.2 and 1.). The minimum pressure ratio, $[P_4/P_e]_{(min)}$, tends to decrease when increasing both N_{g1} and N_{g2} . As N_{g1} goes to infinity, $[P_4/P_e]_{(min)}$ approaches the limiting value for the case when only gas (air) is flowing through the injector. This value can be determined by simple normal shock relations. For N_{g1} varying within the practical limits ($N_{g1} > 30$), $[P_4/P_e]_{(min)}$ shows to be almost independent of N_{g2} .

Figure 5.5 shows a qualitative representation of the plots of $P_4/P_e(max)$ and $[P_4/P_e]_{(min)}$ corresponding to a specific value of N_{g2} . Note that no flow is possible in the region above the curve corresponding to $[P_4/P_e]_{(max)}$ and no flow with discontinuous shock is

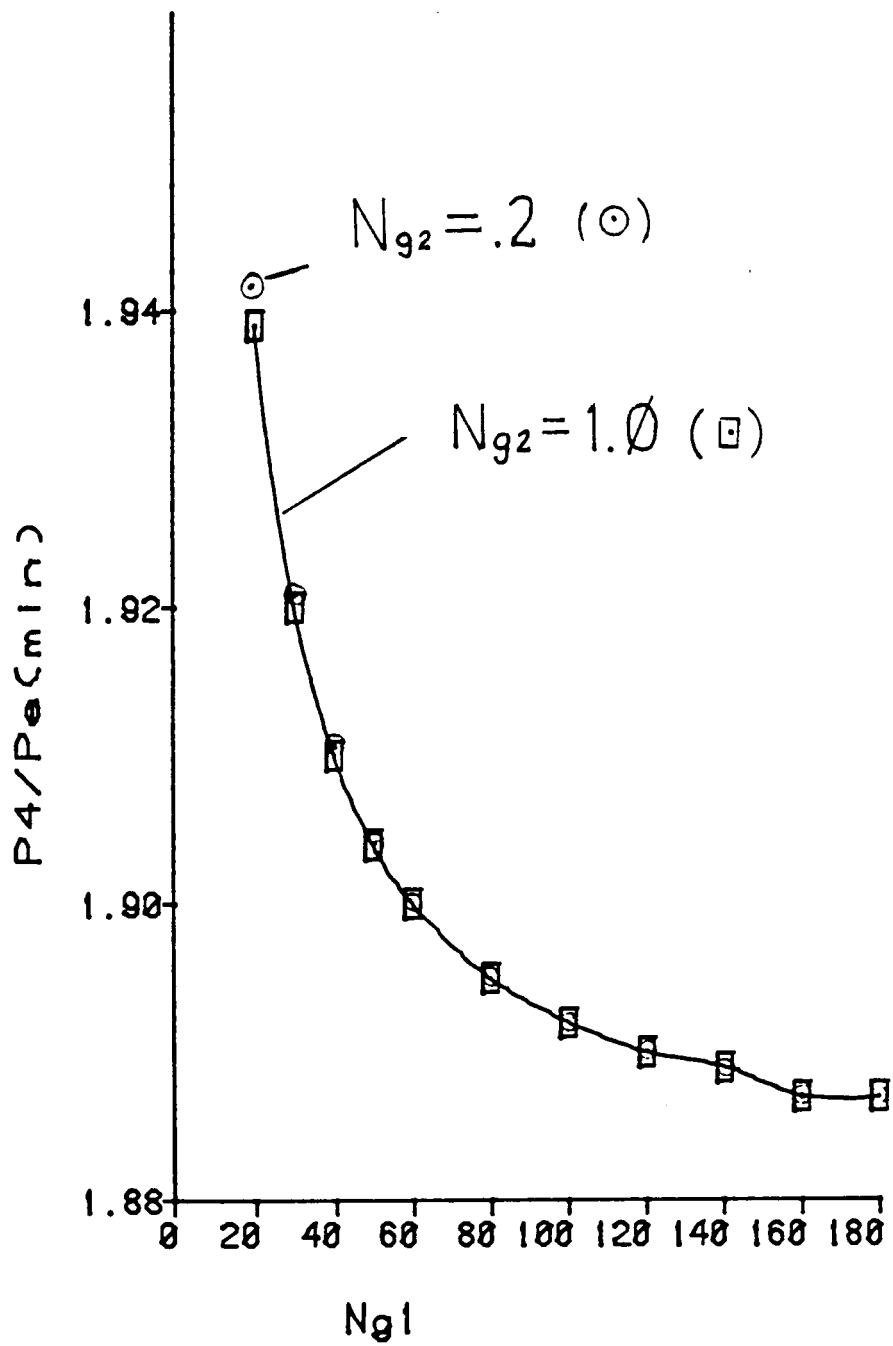


Figure 5.4. Effect the Variation of N_{g1} and N_{g2} on the Lower Limit of P_4/P_e Which Allows the Formation of a Partly-Disperse Shock

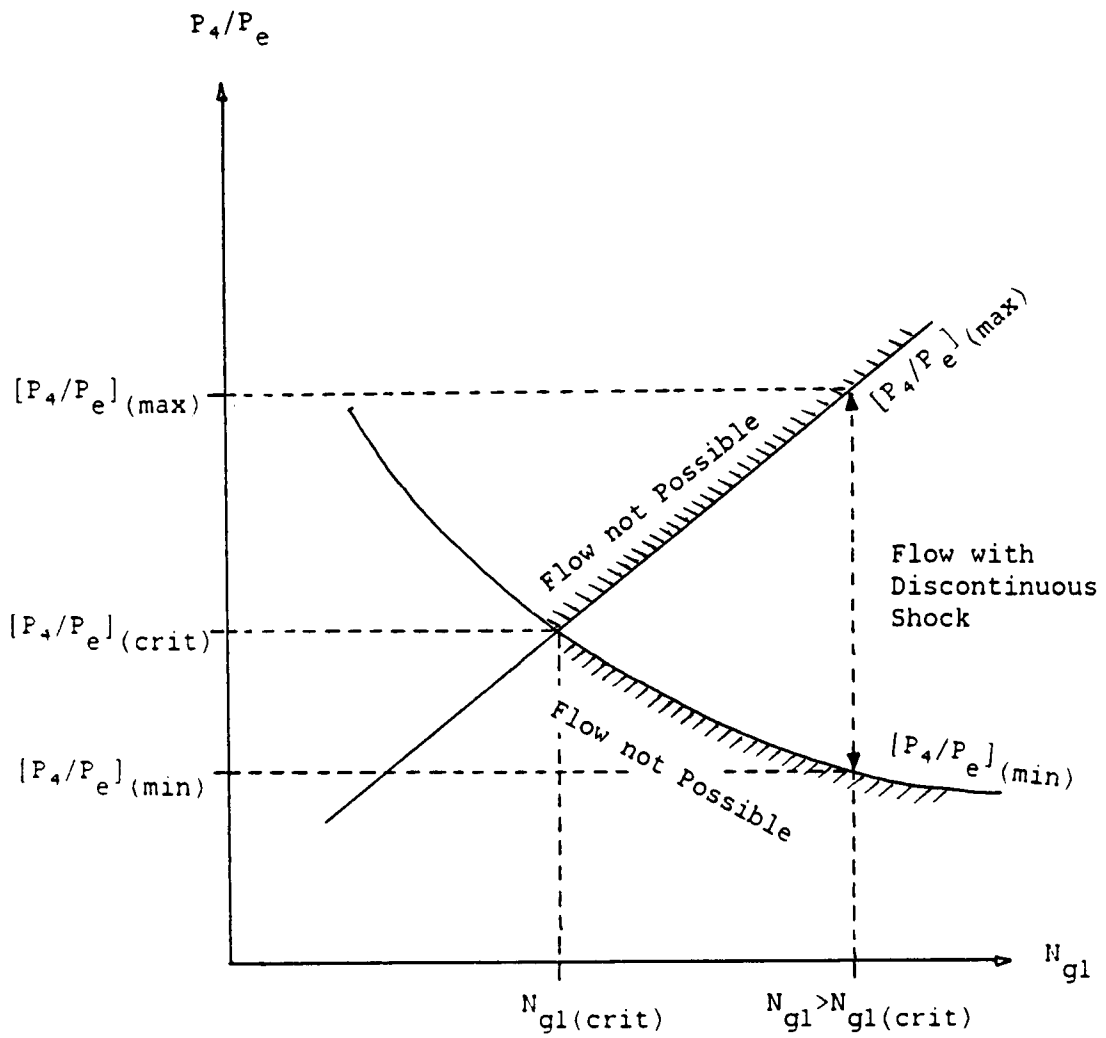


Figure 5.5. Theoretical Limiting Values for N_{gl} and P_4/P_e

possible in the region below the curve corresponding to $[P_4/P_e]_{(min)}$. For a given N_{g1} greater than $N_{g1(crit)}$ there is a range of P_4/P_e between $[P_4/P_e]_{(min)}$ and $[P_4/P_e]_{(max)}$ where a flow is established with a discontinuous shock. Note that depending whether the pressure ratio P_4/P_e is above or below $[P_4/P_e]_{(crit)}$, there is a minimum value of N_{g1} determined by the interception point either with the curve for $[P_4/P_e]_{(max)}$ or with the curve for $[P_4/P_e]_{(min)}$ below which the gas-dynamic injector cannot operate.

Figure 5.6 shows a plot of the area of the injection tube exit section as a function of N_{g2} . This function should approach a linear behaviour as N_{g2} is increased, as may be verified by analyzing eq. (4.41). The parameters R_e , γ_e , and T_e which are involved in the determination of A_e approach finite values as N_{g2} goes to infinity: R_e becomes R , γ_e becomes γ , and T_e , which is a function of M_e , γ_e and T_{0e} becomes constant (M_e and T_{0e} are fixed parameters).

Figures 5.7 show the plots of the area ratios A_4/A_e as a function of the parameters N_{g1} and N_{g2} . As in this case, all the others area ratios (A^*/A_e , A_1/A_e , and A_2/A_e) increase with increasing N_{g1} and decrease with increasing N_{g2} . All these area ratios approach a linear dependency on N_{g1} for large values of N_{g1} . In fact, all of them grow in an almost linearly proportional manner with N_{g1} for N_{g1} greater than 20.

Figure 5.8 shows the effect of increasing the static pressure at the injection tube exit on the overall pressure ratio P_{g1}/P_4 for $N_{g2}=1$ and $T_{0e}=700^\circ K$. (The numerical data is listed in Table C.9.) Note the strong dependency of P_{g1}/P_4 on P_e . For instance, at $N_{g1}=40$, P_{g1}/P_4 drops from 11.32 to 2.816 as P_e is increased from 1 bar to 2 bar. At

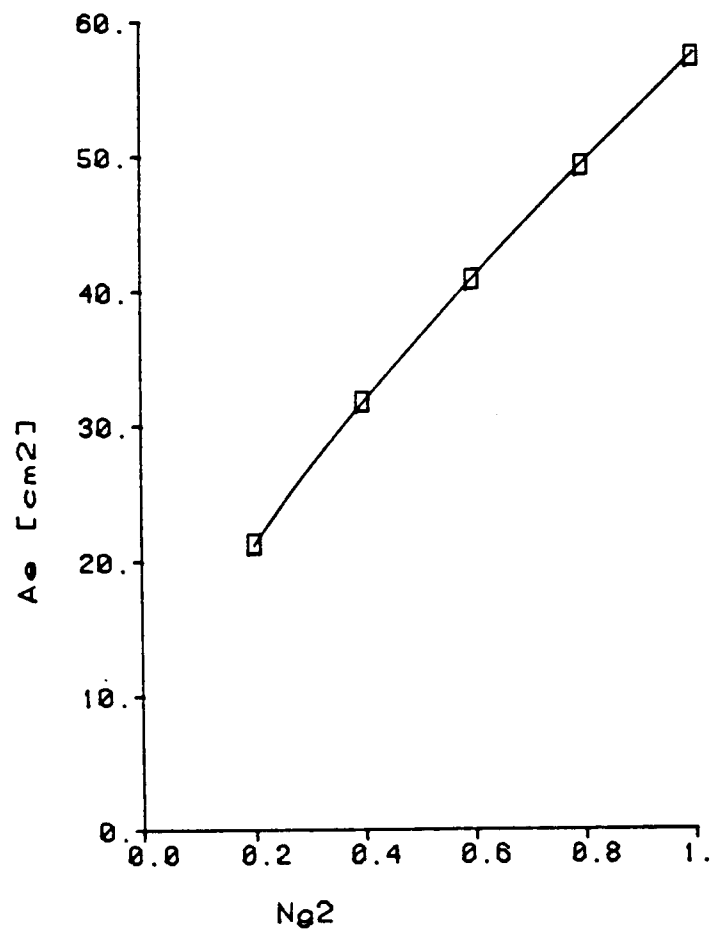


Figure 5.6. Effect of Variation of N_{g2} on A_e

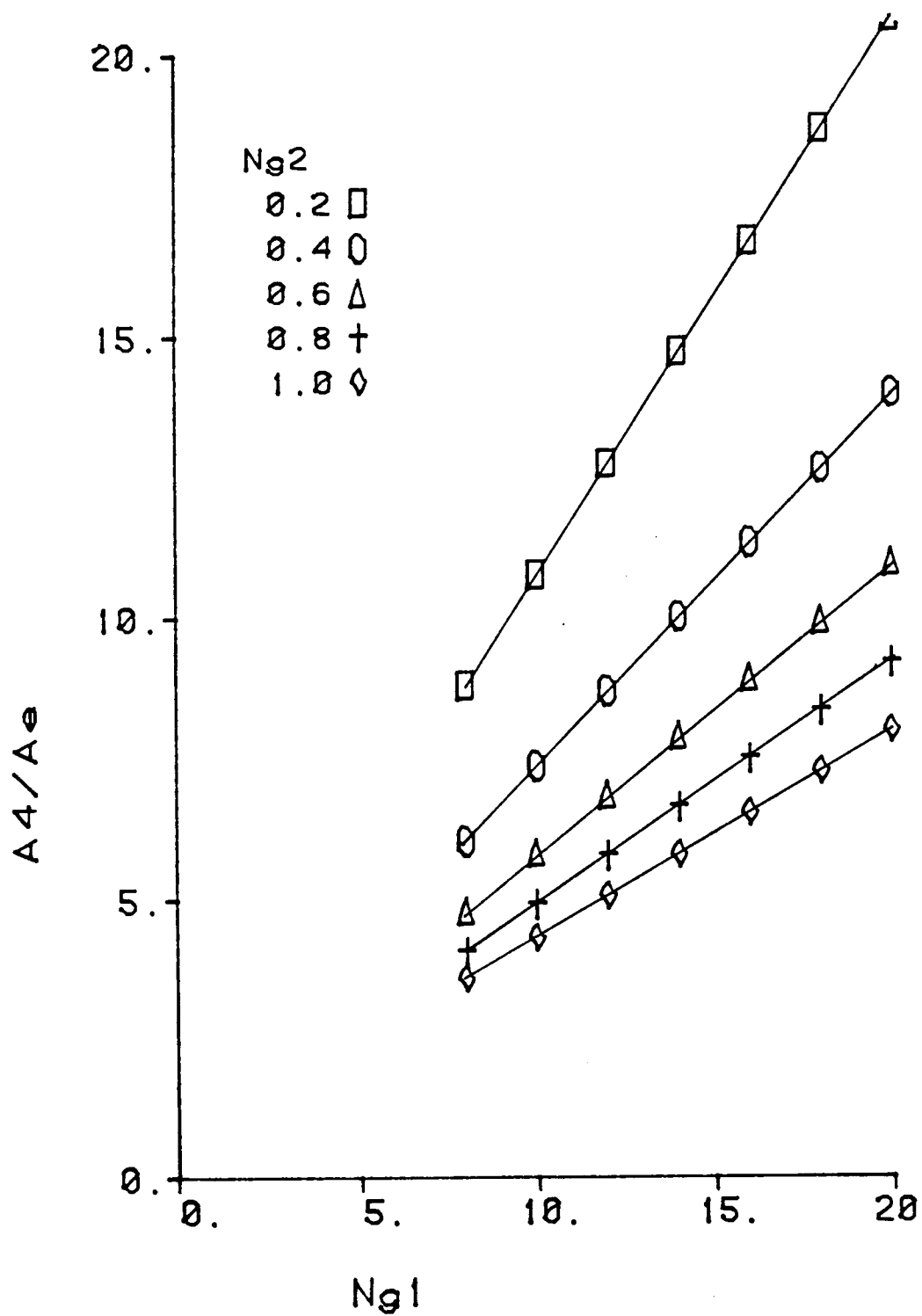


Figure 5.7. Effect of the Variation of N_{g1} and N_{g2} on the Area Ratio A_4/A_e

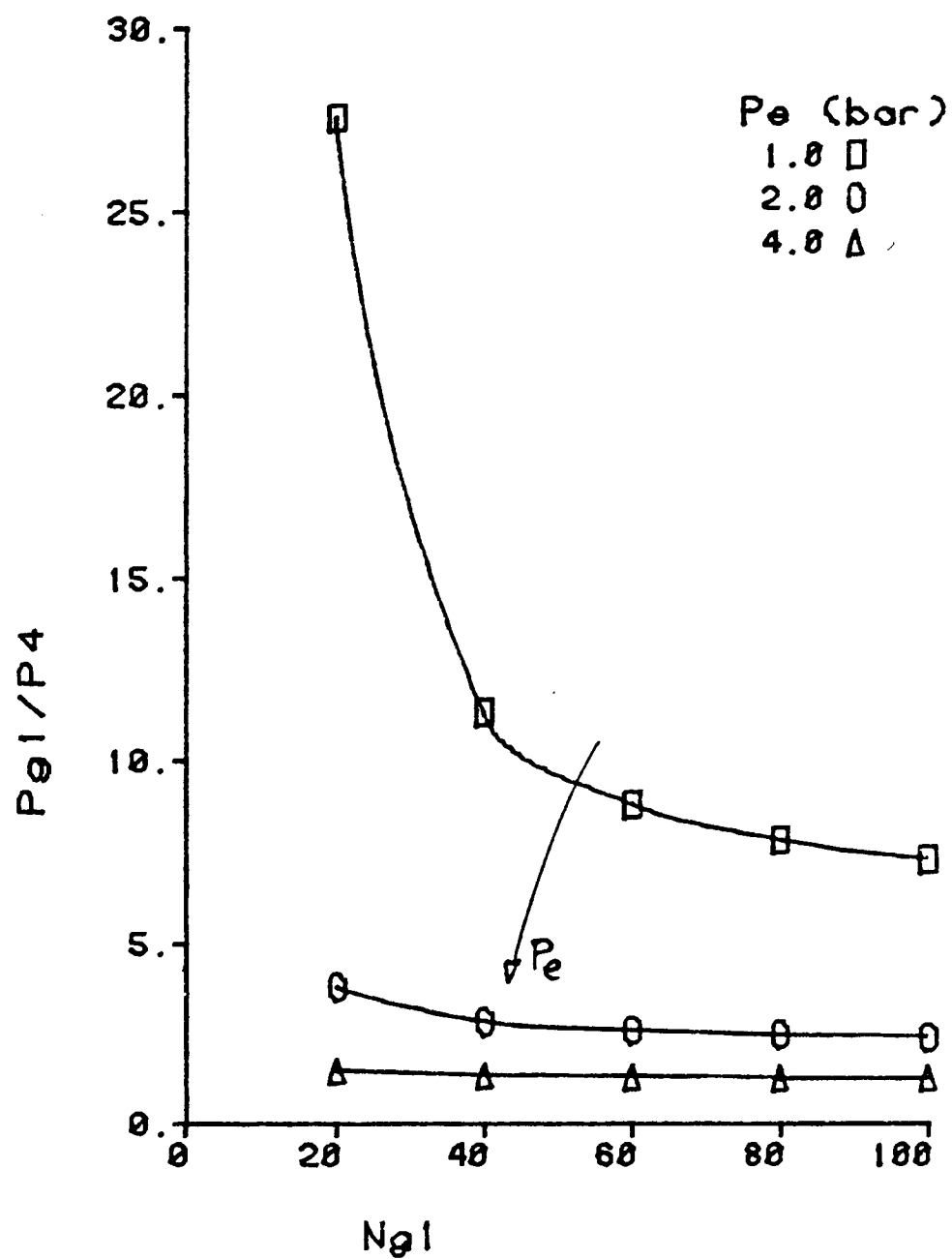


Figure 5.8. P_{g1}/P_4 as a Function of N_{g1} and P_e for $N_{g2}=1$ and $T_{0e}=700^\circ\text{K}$

these conditions the total pressure in the stagnation chamber (50.7 bar) fits within reasonable practical limits. This suggests that a low-pressure differential solids feeder should be used before introducing the gas-solids suspension into the injection tube and the pressure rise across this feeder should be as large as possible. (Reliable low-pressure differential solids feeder are available which handle pressure differentials up to 3 bar approximately.) Note also that P_{g1}/P_4 is almost independent from N_{g1} as P_e is increased over 2 bar.

Figure 5.9 shows the effect of the variation of T_{0e}/T_{g1} on P_{g1}/P_4 . The value of N_{g2} was fixed at 1 and the value of P_e at 1 bar. (The numerical results are in Table C.10.) It can be noticed that P_{g1}/P_4 decreases with T_{0e}/T_{g1} decreasing and that the effect is stronger for smaller values of N_{g1} . As N_{g1} increases P_{g1}/P_4 becomes a weaker function of T_{0e} and, in the limit, the value of P_{g1}/P_4 will approach 5.365 as computed previously for $N_{g1}=\infty$ regardless of the value of T_{0e}/T_{g1} .

Figure 5.10 summarizes the behaviour of all parameters as function of N_{g1} for a fixed N_{g2} . The plots of Figure 5.10 were qualitatively drawn after numerical results were obtained. These results are shown in Table 5.2. They were obtained for the value of $N_{g2}=1$ and for the range of N_{g1} between 7.5 and 7.9. Note that as N_{g1} approaches 7.6 from right to left the ratio P_{g1}/P_4 grows rapidly to infinity. (Actually the limit on N_{g1} is less than 7.6, but close to it.) Meanwhile, the area ratios A^*/A_e and A_1/A_e approach zero and the area ratios A_2/A_e and A_4/A_e approach finite values of .892 and 3.425 respectively. As N_{g1} approaches this limit M_1 approaches infinity. At such conditions the

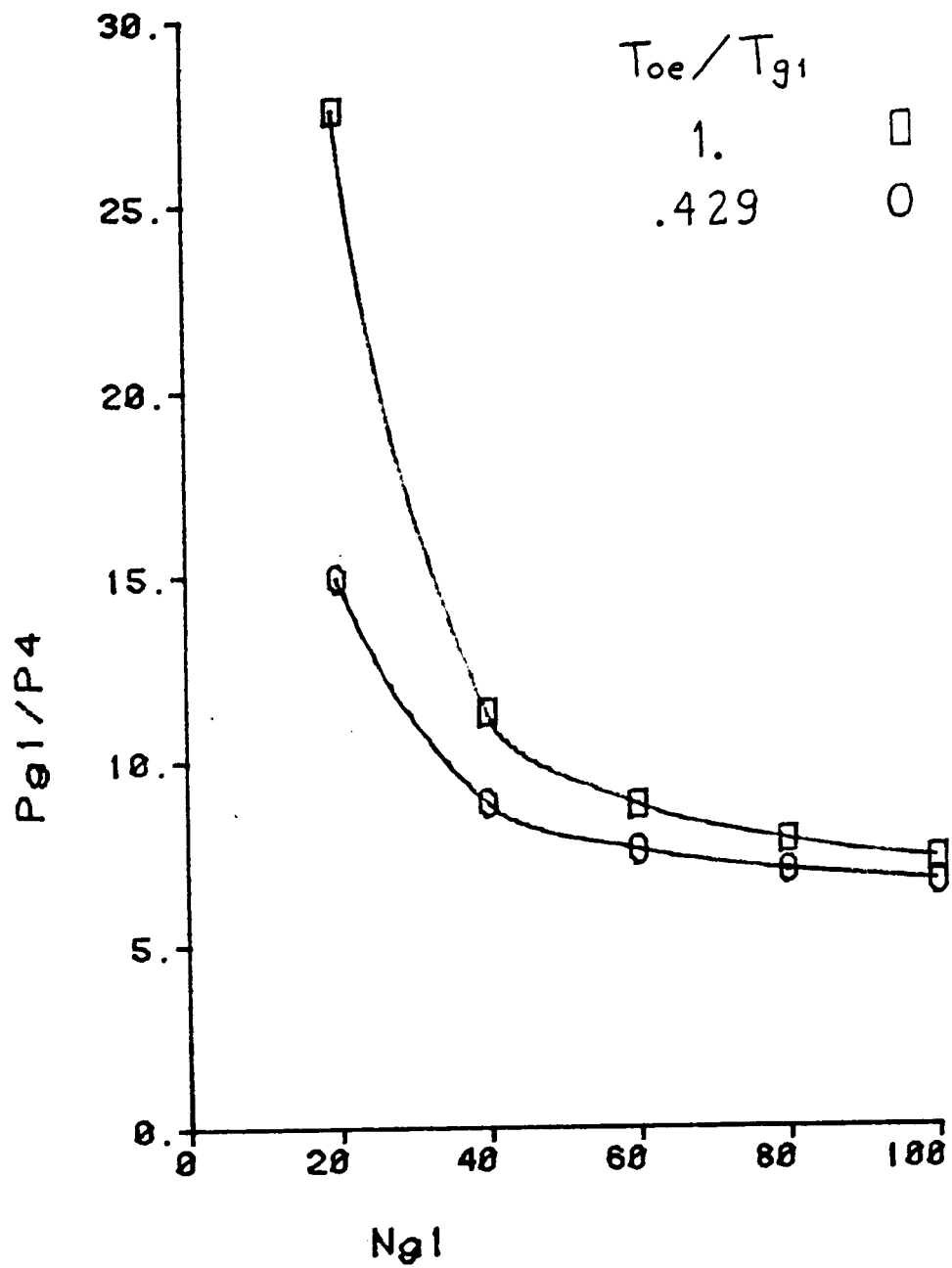


Figure 5.9. P_{g1}/P_4 as a Function of N_{g1} and T_{0e} for $N_{g2}=1$ and $P_e=1$ bar

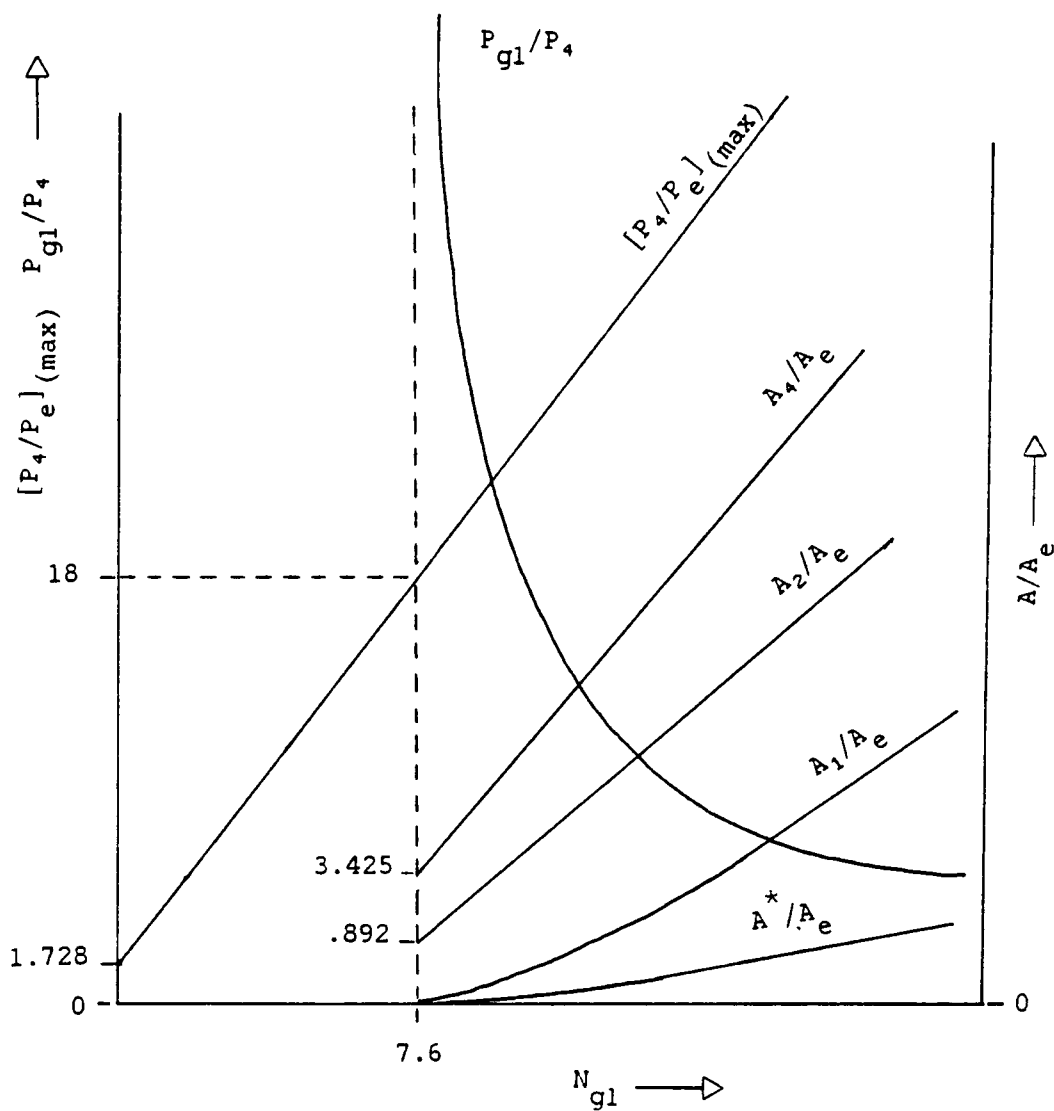


Figure 5.10. Behaviour of the Parameters A^*/A_e , A_1/A_e , A_2/A_e , A_4/A_e , P_{g1}/P_4 , and $[P_4/P_e]_{(max)}$ for $N_{g2}=1$, $T_{0e}=T_{g1}=700^\circ K$, $P_4/P_e=18$, $P_e=1$ bar

Table 5.2. Parameters A^*/A_e , A_1/A_e , A_2/A_e , A_4/A_e , P_{g1}/P_4 , A_e , $[P_4/P_e]_{(max)}$, $[P_4/P_e]_{(min)}$ as Functions of the Primary Gas Nondimensional Mass Flow Rate N_{g1} in the Range $7.5 < N_{g1} < 7.9$

N_{g1}	7.5	7.6	7.7	7.8	7.9
A^*/A_e	--	0.000	0.000	0.000	0.000
A_1/A_e	--	0.001	0.009	0.018	0.026
A_2/A_e	--	0.892	0.902	0.911	0.920
A_4/A_e	--	3.425	3.462	3.499	3.536
P_{g1}/P_4	--	.6856E+11	.1283E+08	.1385E+07	.3701E+06
$[P_4/P_e]_{(max)}$	17.80	18.01	18.21	18.42	18.62
$[P_4/P_e]_{(min)}$	2.029	2.027	2.025	2.024	2.022

($N_{g2}=1$ and $A_e=57.18 \text{ cm}^2$)

GDI operates with the minimum theoretical value of N_{g1} , $N_{g1(min)}$, for the specified values of P_4/P_e and N_{g2} . This value is an absolute lower limit for N_{g1} ; any other practical limit for N_{g1} should be well above it. Note that the power required for the primary gas goes to infinity as N_{g1} either approaches such a lower limit or infinity. Thus, an optimum value of N_{g1} is to be expected such that the power requirements for the primary gas are reduced to a minimum.

In conclusion, a gas-dynamic injector should operate with the minimum possible value of N_{g2} and the maximum possible pressure at the injection tube (P_e). The temperature ratio T_{0e}/T_{g1} should be as small as possible in order to reduce P_{g1}/P_4 . N_{g1} should be kept at an optimum value above $N_{g1(min)}$ at the point of minimum power requirements such that the practical limits of pressure for the primary gas are not exceeded.

CHAPTER 6

THE EXPERIMENTAL STUDY

The purpose of this study was to verify the analytical model of a gas-dynamic injector experimentally. Figure 6.1 shows a schematic view of the gas-dynamic injector experimental model. The subsonic section of the diffuser was not used because the "high" pressure vessel being fed in the experiment was at atmospheric pressure. This placed a lower limit on the minimum pressure (≈ 0) to which the primary gas could be expanded. If a subsonic diffuser was included, such a large percentage of the overall pressure increase in the flow would occur in it such that the shock would be extremely weak. In order to highlight this feature of the device, the entire pressure recovery takes place in a (stronger) shock wave.

Design of the Test Section

Figures 6.2 and 6.3 show side views of the test section of the experimental apparatus. The test section consists of the nozzle body, two parallel side walls of glass, an upper nozzle block, a lower nozzle block, and two mounting flanges. These parts are joined together in what is called the nozzle assembly. An asymmetric nozzle design was selected because (1) the required changes in cross-sectional area are so small that they can be more accurately controlled if they are due to changes in a single wall (2) no redrilling of pressure taps are required every time the nozzle blocks are replaced. The nozzle upper block is a

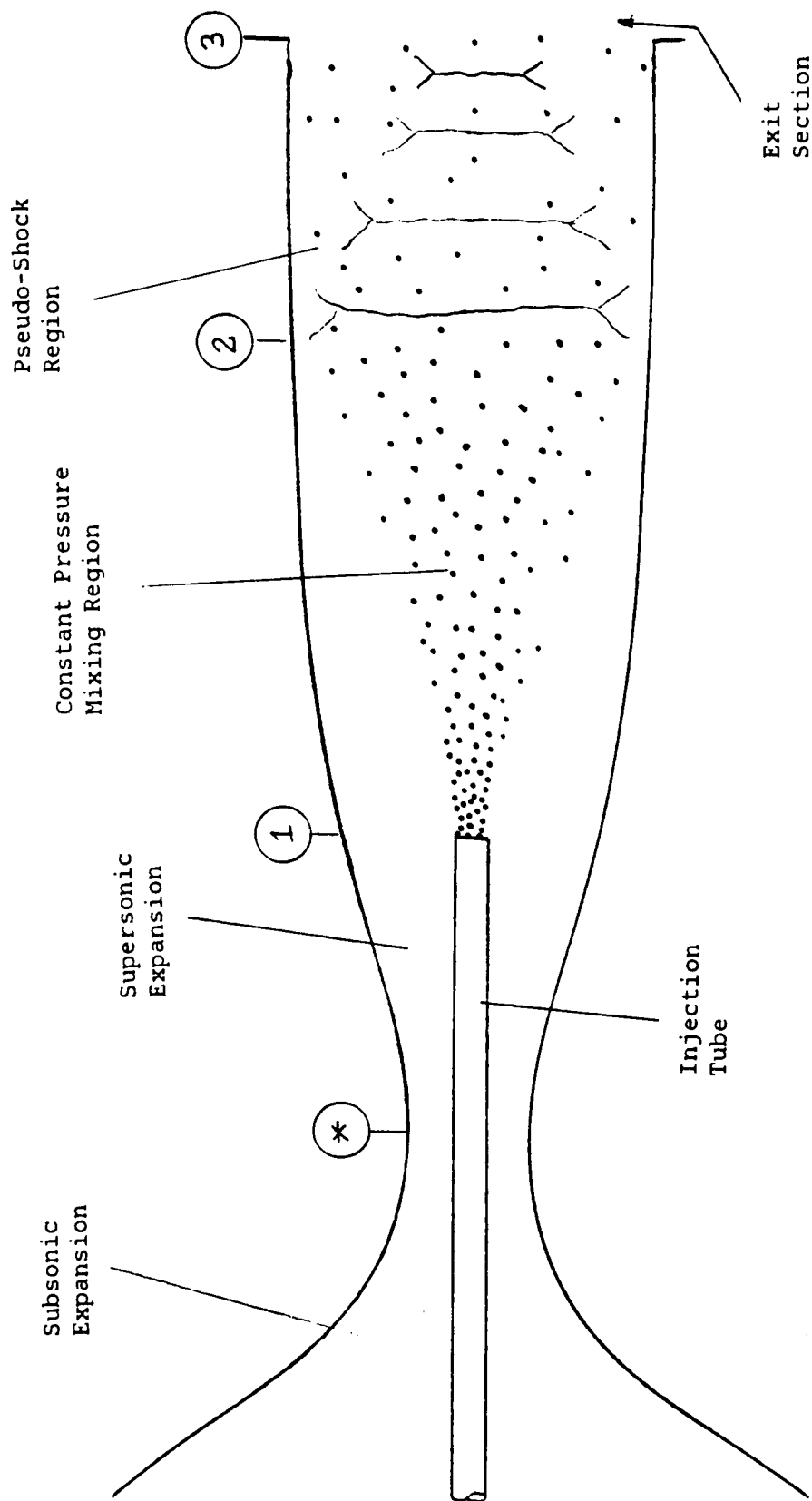


Figure 6.1. Schematic View of the Gas-Dynamic Injector Modified for the Experimental Investigation

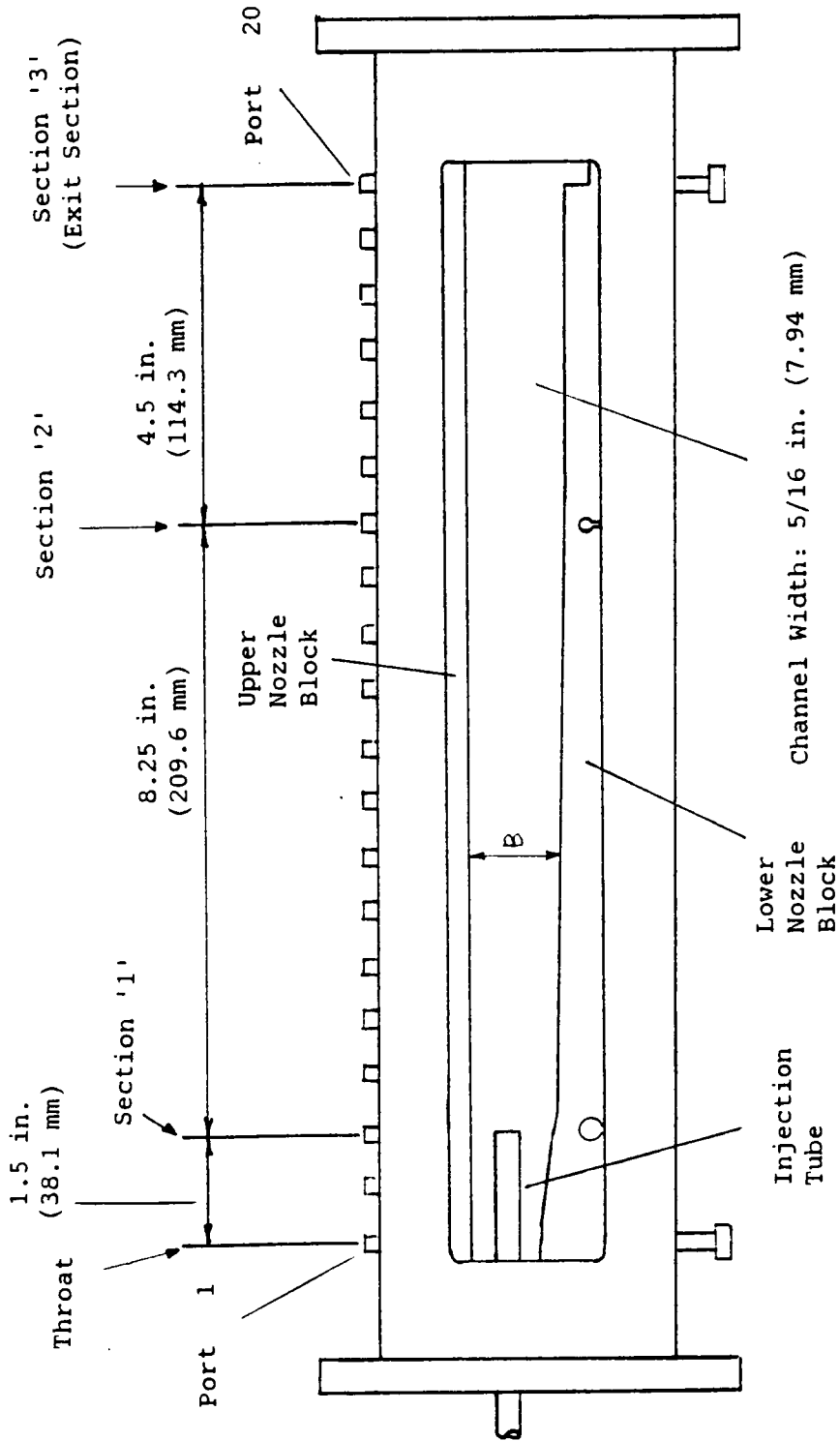


Figure 6.2. Side View of Assembled Test Section

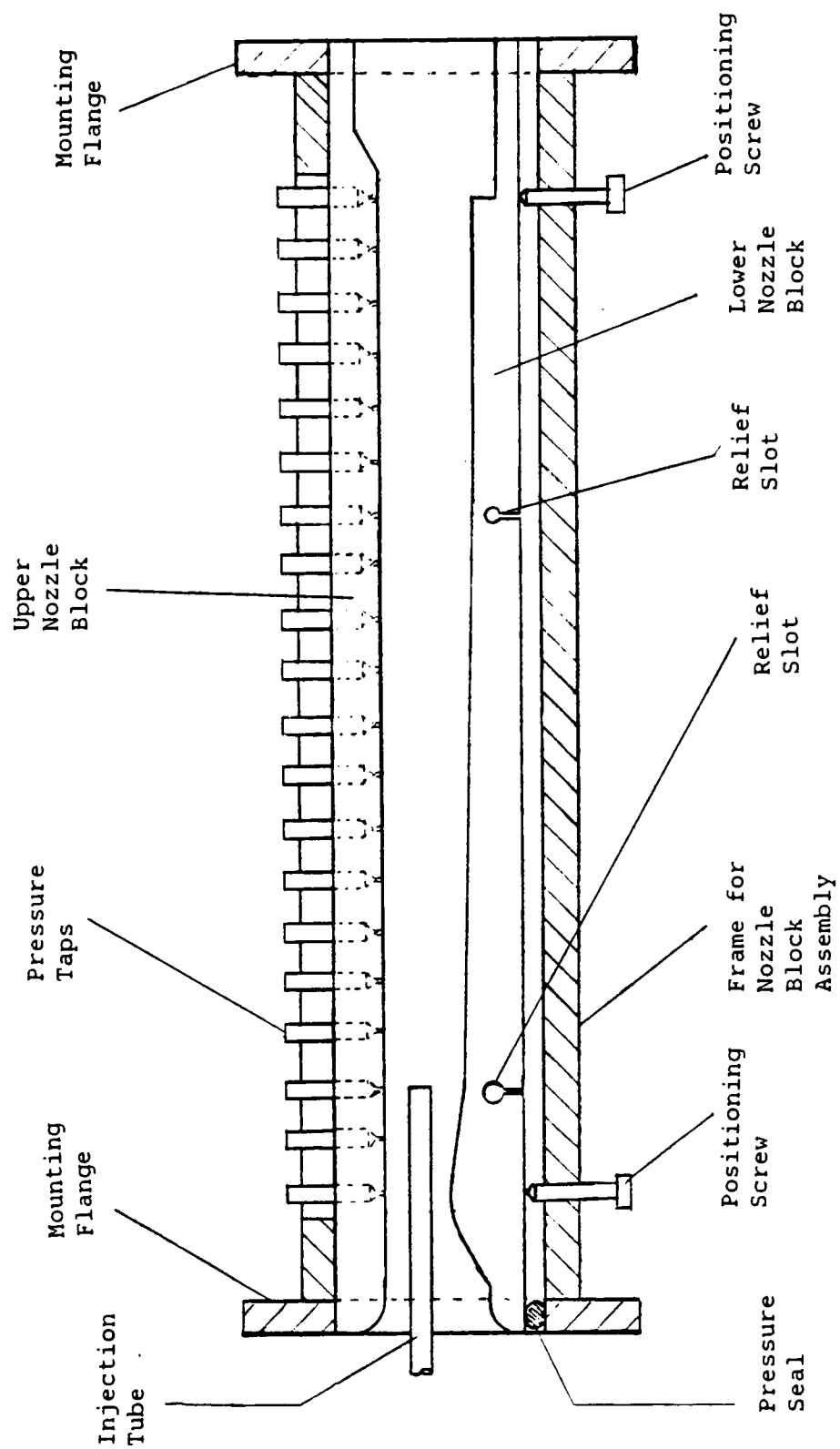


Figure 6.3. Cutaway View of Test Section

straight wall that contains twenty pressure taps. The separation between pressure taps (ports) is .75 inches. The lower nozzle block is shaped to the desired contour and can be tilted or moved up or down by using two positioning screws located at the throat and exit sections. The separation between these two blocks is called the nozzle vertical spacing. The nozzle block thickness, which is equal to the channel width (separation between the two vertical side walls), is 5/16 of an inch (7.94 mm). The upper and lower nozzle blocks are made up of aluminum for ease in construction. The throat coincides with port number one and the exit section coincides with port number twenty.

The simplified mathematical model assumes that the primary and secondary flows are perfectly mixed between sections '1' and '2' independently of the distance between these sections, and that the finite length pseudo-shock between sections '2' and '3' may be modeled as a single discontinuity (normal shock). In a more realistic model these lengths would have to be calculated and/or estimated from empirical results. For the purpose of the experimental study, arbitrary lengths were chosen between the throat and section '1', between sections '1' and section '2', and between section '2' and '3'. These lengths are 1.5 inches, 8.25 inches and 4.25 inches respectively.

The glass windows permit visualization of the flow in the injector. The contour of the lower nozzle block was chosen without using the method of characteristics. An arbitrary shape was given between the throat and section '1'. Straight lines were employed between sections '1' and '2' and between sections '2' and '3'. Figure 6.4 shows a

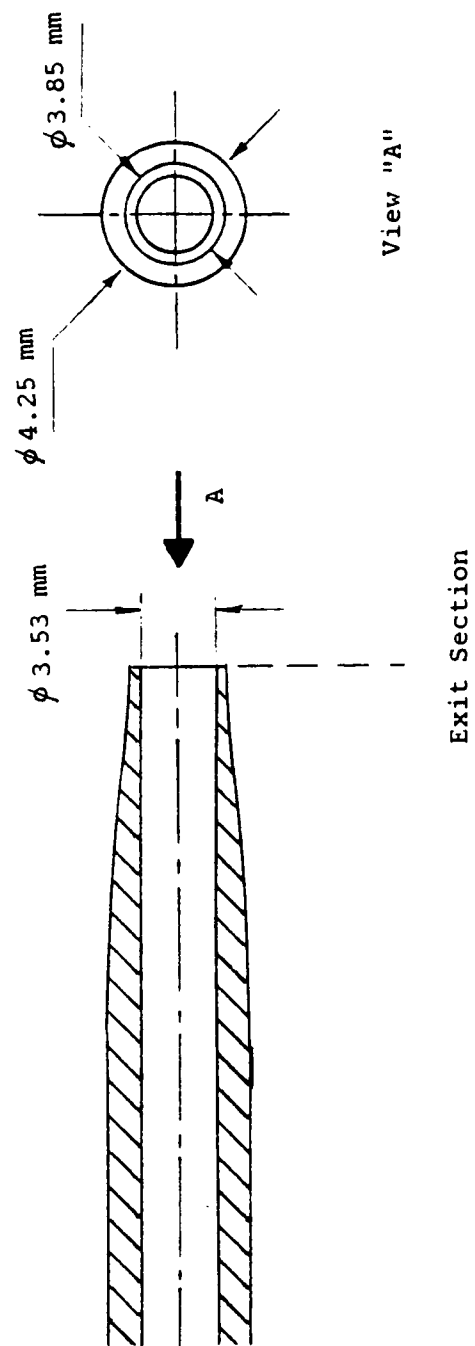


Figure 6.4. Injection Tube Dimensions

detailed view of the injection tube exit section. The thickness of the tube was reduced and its external contour was shaped so that the external stream is parallel to the internal stream at the exit point. The exit section of the injection tube is positioned at port 3 (1.5 inches downstream from the throat).

Selection of Test Conditions

Some of the test conditions are restricted due to physical limitations of the experimental facility while others can be arbitrarily specified. Compressed air at ambient temperature was used as the source of both primary and secondary gas. The powdered solids used for testing were glass beads (glas-shot-type MS-XLWP micro beads, Ferro Corp., Cathapote Div.) because (1) they do not present any fire or explosion hazard, (2) they are relatively clean to handle, and (3) they present a uniform size distribution. These glass beads present the following specifications:

Average Diameter $D_p = .030 \text{ mm},$

Density $d = 2500 \text{ Kg/m}^3 .$

The Mach number at section 'e' and the pressure ratio across the shock were arbitrarily selected as:

$$M_e = 1$$

and

$$P_3/P_e (=P_3/P_2=P_3/P_1) = 2 .$$

The internal cross-sectional area of the injection tube is also a fixed parameter and its value is $A_e = 9.787 \text{ mm}^2$. The external cross-sectional

area of the injection tube at the throat and at the exit section are 14.187 mm² and 11.639 mm² respectively. The values of N_{g1} and N_{g2} were selected so that the mass flow rates of solids and gases could be handled by the experimental apparatus. Their values were:

$$N_{g1} = 20$$

and

$$N_{g2} = .35 .$$

Other experimental parameters such as the stagnation temperatures of the primary and secondary air, the temperature of the solids, and the exhaust (back) pressure that cannot be controlled in the present experimental set up are measured in each test. The temperature of the solids and the stagnation temperatures of the primary and secondary air are approximately the same as the atmospheric temperature at the time a test is run. The values of these temperatures ranged from 294°K to 298°K. The exhaust pressure was .920 bar $\pm$.005 bar. Since the exhaust pressure remained approximately constant, a value of $P_3 = .920$ bar was used to design the nozzle. A list of the fixed parameters used for the calculations are in Table 6.1. Calculations were made for five values of the temperature T_{g1} ($=T_{0e}$) between 294°K and 298°K.

The cross sectional areas of the experimental device were determined by using a version of the theoretical model derived in Chapter 5 which does not include the subsonic diffuser. A listing of the nozzle block design program, GDIND, is given in Appendix E. When run in mode "3", this program outputs all the cross sectional areas, mass flow rates, and the stagnation pressure of the primary air. Table 6.2

Table 6.1. Fixed Parameters Used in the Experimental Study

Ratio of Specific Heats of Air	$\gamma = 1.4$
Gas Constant of Air	$R = 287. \text{ N-m/Kg-K}$
Ratio of Specific Heat of Glass to Constant-Pressure Specific Heat of Air	$c/c_p = .75$
Density of Glass Beads	$d = 2500. \text{ Kg/m}^3$
Nondimensional Mass Flow Parameter of Primary Air	$N_{g1} = 20$
Nondimensional Mass Flow Parameter of Secondary Air	$N_{g2} = .35$
Inlet Pressure of Gas-Solids Suspension	$P_e = .460 \text{ bar}$
Inlet Pressure of High-Pressure Vessel	$P_3 = .920 \text{ bar}$
External Cross-Sectional Area at Section '*'	$A^*_{(ext)} = 14.187 \text{ mm}^2$
External Cross-Sectional Area at Section '1'	$A_{1(ext)} = 11.639 \text{ mm}^2$
Nozzle Width	Width = 7.94 mm
Mach Number at Injection Tube Exit Section	$M_e = 1.$

and 6.3 show the results given by the program GDIND. Table 6.2 lists the theoretical values of the parameters which are independent of the temperature, namely, the cross-sectional areas, the nozzle vertical spacings, the Mach numbers, and the static and the stagnation pressures. Note that because the geometry of the injection tube is specified, the geometry of the injector is fixed. This is true for the present design conditions where the total temperatures of all flows involved (T_{g1} and T_{0e}) are equal. (Changes in the total temperature affect only the mass flow rates of those flows.) Consequently, all Mach numbers and pressure ratios are independent of T_{g1} . Table 6.3 shows the theoretical values of the mass flow rates of primary gas, secondary gas and solids as functions of the total temperature. It may be noted that the variation in the total temperature within the range 294°K-298°K does not cause appreciable variations in the values of these parameters.

Instrumentation and Data Acquisition

The experimental variables that had to be measured for each test are the mass flow rate of solids, the mass flow rate of the primary air, the mass flow rate of the secondary air, the pressure in the stagnation chamber, and the pressure distribution along the nozzle. The desired mass flow rate of solids is obtained by calibrating the solids feeder immediately before the test is run. The mass flow rates of the primary and secondary air are determined once the pressures, temperatures, and volumetric flow rates are known. The volumetric flow rates are measured with the two Rotameter flowmeters. The pressure and

Table 6.2. Theoretical Results of Parameters Independent of the Total Temperature for $T_{0e}/T_{g1}=1$

Section--> (THROAT)		1	2	3	e	
A	[mm ²]	141.3500	157.2435	170.9522	170.9522	9.7871
B	[mm]	19.60	21.28	21.54	21.54	
M		1.0000	1.3955	1.3646	0.7543	1.0000
P	[bar]	.768	.460	.460	.920	.460
P ₀	[bar]	1.455	1.455	1.382	1.336	.787

(B computed for nozzle width = 7.94 mm.)

Table 6.3. Values of the Mass Flow Rates and Solids Volume Fraction as Functions of T_{g1} for $T_{0e}/T_{g1}=1$

		Temperature ($T_{g1}=T_{0e}$) [°K]				
		294	295	296	297	298
Mass Flow Rates						
[g/s]						
Primary Air		48.46	48.38	48.30	48.22	48.14
Secondary Air		.848	.847	.845	.844	.842
Solids		2.423	2.419	2.415	2.411	2.407
Solids Volume Fraction						
Section '3' (x1.E3)		.238	.237	.236	.235	.234
Section 'e' (x1.E4)		.654	.652	.650	.648	.645
Static Temperature						
[°K]						
Section '*'		245.00	245.83	246.67	247.50	248.33
Section '1'		211.59	212.31	213.03	213.75	214.47
Section '2'		217.11	217.85	218.58	219.32	220.06
Section '3'		265.30	266.20	267.10	268.00	268.91
Section 'e'		280.00	280.95	281.90	282.86	283.81

temperature are measured at the exit section of both Rotameters. All pressure terminals are connected to a device called the "Scanivalve" which is a pressure transducer designed to handle pressure signals from as many as 48 ports. The temperature is measured by thermocouples. A data acquisition and control unit (DA/C unit HP 3497A) receives all transduced signals of pressure and temperatures. A computer (HP 9826) connected to the DC/A unit processes the information received from the DC/A unit. (See Appendix F for a detailed description of the experimental apparatus and specifications.) A program in BASIC language was written to be run by the HP 9826 in order to perform automatic data measurement and recording. (This program is listed in Appendix G.) The program performs computation of mass flow rates and plots the pressure distribution along the channel. The errors in measurement of all variables and the uncertainty analysis are given in Appendix I.

Evaluation and Development of the Experimental Apparatus and Techniques

Before the final test was run a number of attempts were made to obtain the desired conditions of mass flow rates and pressure ratio across the shock. The first step was to adjust the nozzle contour according to the theoretical results and try to match experimental values of mass flow rates of all flows with their respective theoretical values. Table 6.4 contains the experimental values of the mass flow rates, temperatures, nozzle vertical spacings and pressures. All temperatures and mass flow rates match their respective theoretical

Table 6.4. Experimental Values of the Mass Flow Rates, Temperatures, and Total Pressure in the Stagnation Chamber for Nozzle Designed with Theoretically-Computed Values

Definition of Variable	Experimental Value	Theoretical Value	Percent Error
Stagnation Temperature of Primary Gas (T_{g1}) [°K]	294.1	295.0	-.3
Stagnation Temperature of Secondary Gas (T_{g2}) [°K]	295.9	295.0	.3
Temperature of Solids (T_p) [°K]	295.0	295.0	.0
Stagnation Pressure of the Primary Air (P_{g1}) [bar]	1.595	1.455	9.6
Mass Flow Rate of Primary Gas ($\dot{m}_{g1}$) [g/s]	47.3	48.38	-2.2
Mass Flow Rate of Secondary Gas ($\dot{m}_{g2}$) [g/s]	.84	.847	-.8
Mass Flow Rate of Solids ($\dot{m}_p$) [g/s]	2.4	2.419	-.8
Vertical Spacing Between Nozzle Blocks [mm]:			
B^*	19.60	19.60	.00
B_1	21.30	21.28	.09
B_2	21.55	21.54	.05
B_3	21.55	21.54	.05
Static Pressures [bar]:			
P^*	1.158	.768	50.7
P_1	1.136	.460	146.9
P_2	1.025	.460	122.8
P_3	.918	.920	-.2

values within less than 3 percent error. The total pressure in the stagnation chamber was 1.595 bar instead of 1.455 bar (9.6 percent above theoretical value). The pressure readings for each port along the injector are listed in Table H.1. The pressure distribution along the injector is shown in Figure 6.5. Note that the static pressure at the injection tube exit plane ($P(3)=1.136$ bar) is above the theoretical value (.46 bar) and also above the exit pressure (.918 bar). Examination of the numerical value of P^*/P_{g1} reveals that the flow does not reach sonic conditions at the throat. P^*/P_{g1} , whose value is .726, is well above the theoretical value for air which is .5283 (isentropic tables). The fact that the flow throughout the nozzle is entirely subsonic was verified by visualizing the flow with the Schlieren system. No shocks were observed anywhere. It is obvious that the viscous effects which were not accounted for in the derivation of the mathematical model were causing large enough losses to prevent the desired (supersonic) flow from being established. Thus, the second step was to establish a supersonic flow inside the injector by increasing the pressure in the stagnation chamber. For this test the flows of solids and secondary air were shut off so that the loss of momentum of the primary gas was reduced to a minimum.

Table 6.5 contains the experimentally-determined values of the mass flow rates, temperatures, nozzle vertical spacings, and pressures for the injector having the theoretically computed contour and higher than theoretical value of the stagnation pressure. The pressure readings along the injector are listed in Table H.2. Figure 6.6 shows these

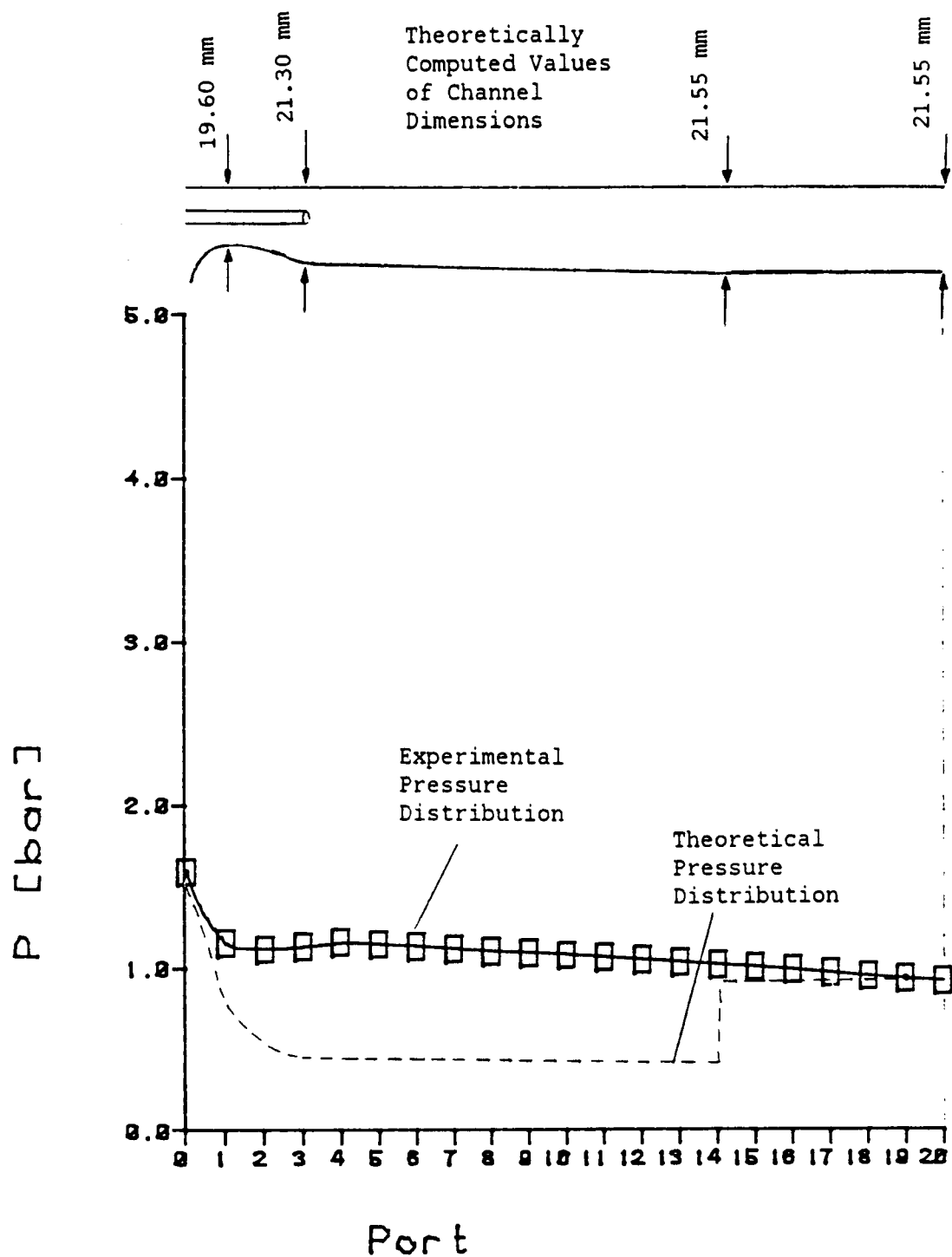


Figure 6.5. Experimentally-Determined Pressure Distribution for Gas-Dynamic Injector with Experimental Values of Cross-Sectional Areas and Mass Flow Rates Closely Matching Theoretical Values

Table 6.5. Mass Flow Rates and Remperatures Measured During Test Using Theoretically-Computed Cross-Sectional Areas and Higher-than-Theoretical Value of Pressure in the Stagnation Chamber

Definition of Variable	Experimental Value	Theoretical Value	Percent Error
Stagnation Temperature of Primary Gas (T_{g1}) [°K]	297.1	297.0	.03
Stagnation Temperature of Secondary Gas (T_{g2}) [°K]	297.3	297.0	.10
Temperature of Solids (T_p) [°K]	295.0	297.0	-.67
Stagnation Pressure of the Primary Air (P_{g1}) [bar]	4.394	1.455	202.0
Mass Flow Rate of Primary Air ($\dot{m}_{g1}$) [g/s]	142.0	48.22	194.5
Mass Flow Rate of Secondary Air ($\dot{m}_{g2}$) [g/s]	.00	.844	-100.0
Mass Flow Rate of Solids ($\dot{m}_p$) [g/s]	0.0	2.411	-100.0
Vertical Spacing Between Nozzle Blocks [mm]:			
B^*	19.60	19.60	.00
B_1	21.30	21.28	.09
B_2	21.55	21.54	.05
B_3	21.55	21.54	.05
Static Pressures [bar]:			
P^*	2.777	.768	261.5
P_1	1.719	.460	273.7
P_2	2.440	.460	430.4
P_3	1.750	.920	90.2

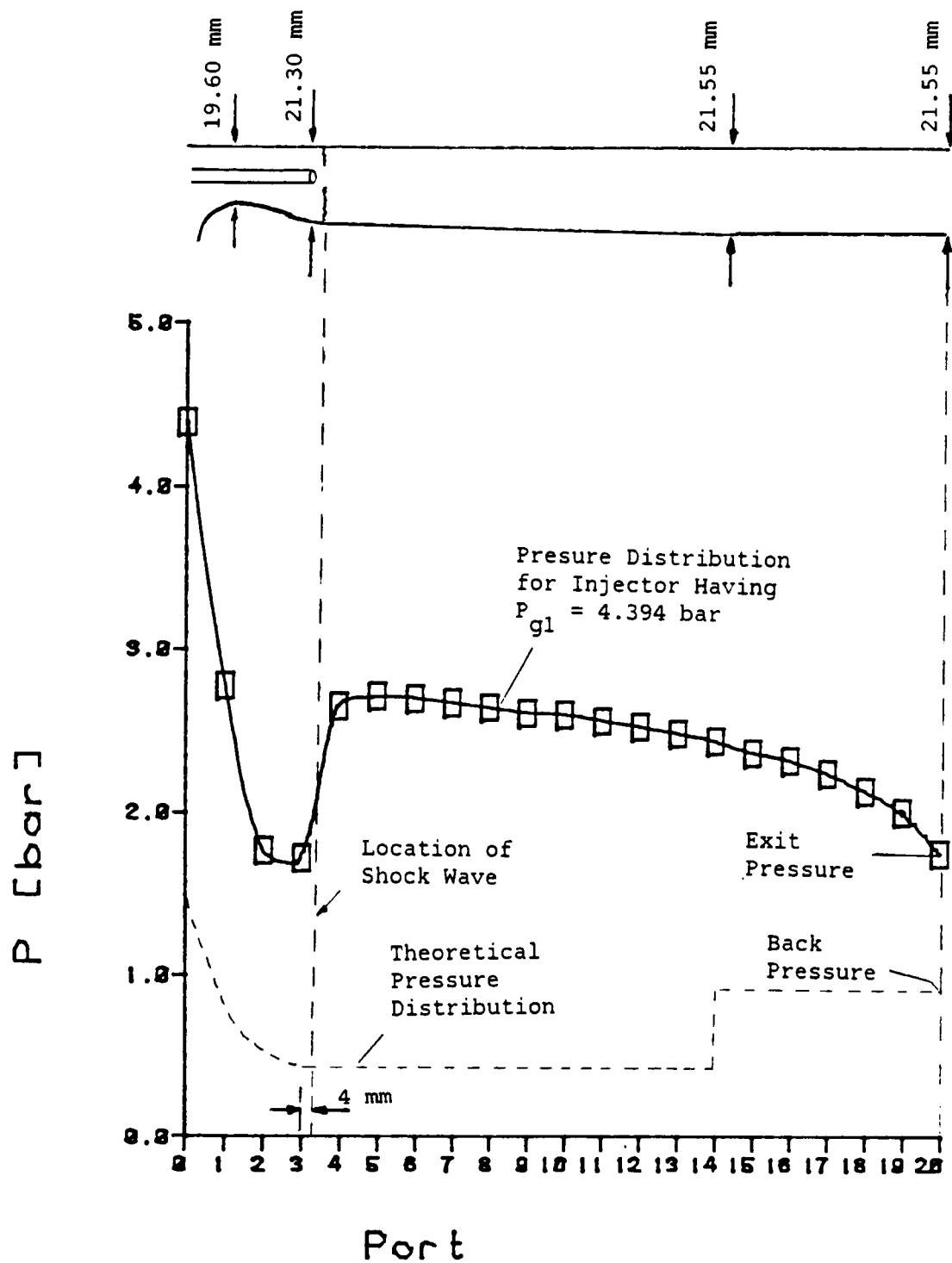


Figure 6.6. Pressure Distribution for Gas-Dynamic Injector Having Theoretically-Computed Cross-Sectional Areas and an Overpressurized Stagnation Chamber

results graphically. The pressure in the stagnation chamber was increased up to about 4.39 bar and a shock wave did appear but it could not be moved further downstream than the midway between ports 3 and 4. The location of the shock is clearly indicated by the pressure distribution of Figure 6.6. It can be noted that in this case the exit pressure (1.75 bar) is higher than the back pressure (.92 bar). This suggests that the flow at the exit is sonic and underexpanded. Therefore, no further increase in stagnation pressure could possibly move the shock downstream of its location between ports 3 and 4. Since the back pressure is always approximately equal to the atmospheric pressure, the flow expands from the high exit pressure to the atmospheric pressure by expansion waves (not observed in this study because they were in a region that could not be viewed).

The results of this experiment show that: (1) pressure losses due to viscous effects are too large to be neglected in the experimental apparatus and (2) the flow in the mixing section behaves like a Fanno-line flow where a subsonic flow reaches sonic conditions at the exit section of the channel. The only possible way to move the shock downstream is by modifying the geometry of the channel. The shock will move downstream only if the area ratios A_3/A^* and A_2/A^* are enlarged. The following is a discussion of the method used to obtain the desired flow conditions in the injector.

Figure 6.7 qualitatively illustrates modifications in the nozzle contour by which a constant pressure mixing region is established and the theoretical pressure ratio across the shock is matched in the

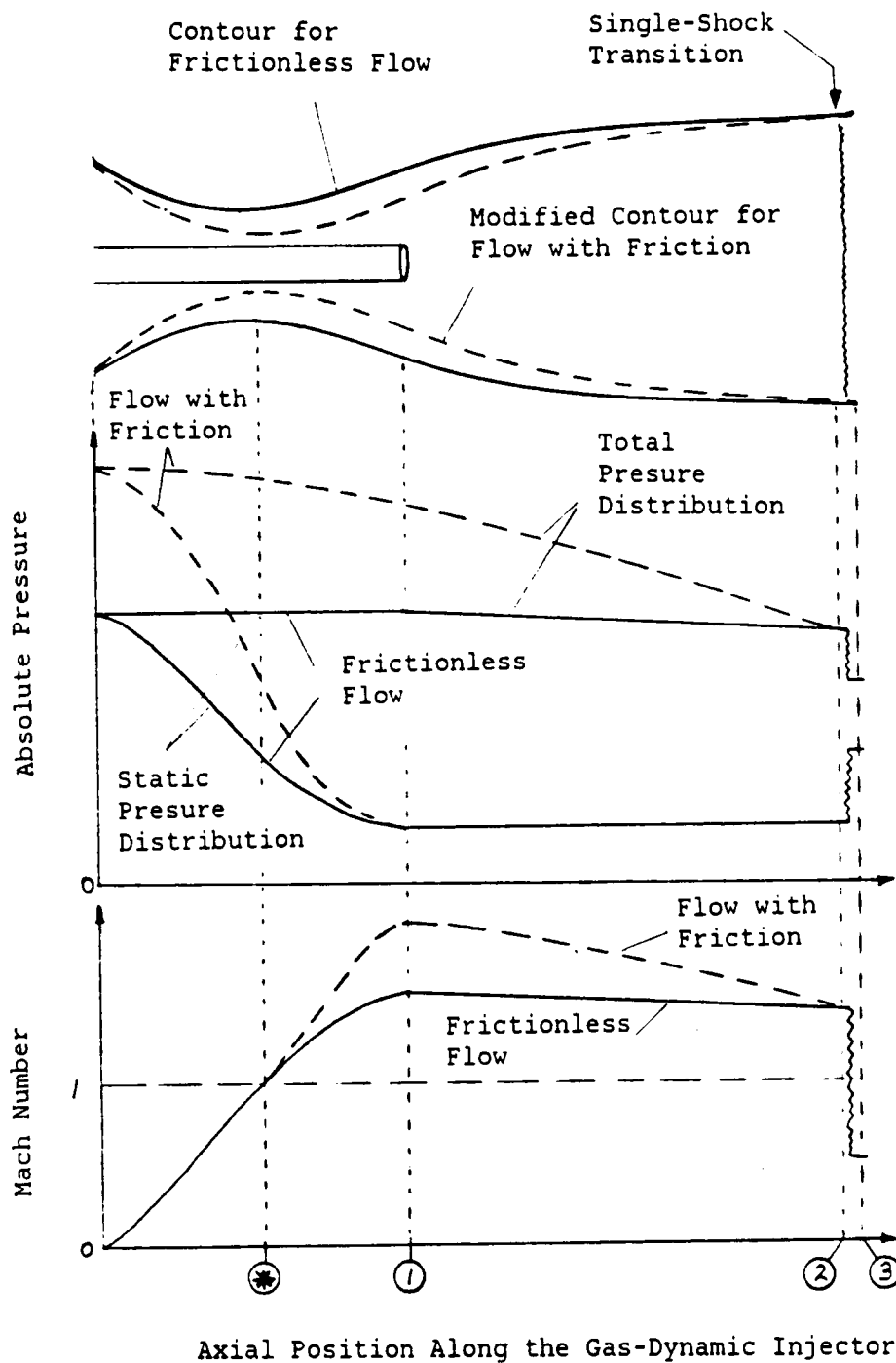


Figure 6.7. Pressure and Mach Number Distributions for Flows with and without Friction (— : Frictionless Flow; ---- : Flow with Friction)

experimental device. The following analysis assumes that the mass flow rate of solids is negligible compared to the mass flow rate of the primary air, which is reasonable since $N_{g1}=20$. The total and static pressure distribution, as well as the Mach number distribution, are shown for both the frictionless flow model and for the experimental model in Figure 6.7. The idea is to reduce the area of the throat and the area of section '1' and at the same time to increase the total pressure in the stagnation chamber. This causes, the total pressure at section '2' immediately upstream of the shock to drop until it matches its theoretical value. Note that there is a larger drop of static pressure through the converging-diverging nozzle (upstream region of the injection tube exit plane) in the experimental case. Since the total pressure at section '1' is higher than its corresponding theoretical value at that section, the Mach number at that same section has to be greater than the theoretical Mach number as shown in the Mach number distribution. That is, when viscous effects are considered, the primary air must enter the mixing region at a higher velocity than in the frictionless flow in order to compensate for the deceleration effect produced by the friction at the walls during the mixing process. Since the injection tube geometry is not changed, and the static pressure at section '1' has the same value as given for the theoretical analysis, the mass flow rate of solids and secondary air need not be changed. As the primary air moves downstream from section '1' the Mach number decreases until it matches its corresponding theoretical value at section '2'. In general, the static pressure at section '2' is

primarily affected by the area ratio A_3/A^* (or A_2/A^*), as is the pressure ratio across the shock. The slope of the pressure plot between sections '1' and '2' is affected by the ratio A_3/A_1 (or A_2/A_1). As A_3/A^* is increased the pressure P_2 decreases and the pressure ratio across the shock increases (the back pressure P_3 is a constant parameter). As A_3/A_1 is increased the static pressure at section '1' also is increased. The method for obtaining an adequate channel contour then is to first adjust A^* until the desired pressure ratio across the shock is obtained and then to adjust A_1 until the pressure is constant between sections '1' and '2'. The results of an additional test which was conducted in order to verify the above procedure are discussed next.

Experimental Results

In order to match experimental and theoretical values of the pressure ratio across the shock and the mass flow rates, an iteration process was conducted by modifying the nozzle contour and adjusting the flow inlet conditions. Table 6.6 lists the data concerning mass flow rates, temperatures, channel vertical spacings, and pressures for the final flow configuration. Note that the averaged value of mass flow rate of the primary air (50.7 g/s) agrees with the theoretical value to within less than 5 percent. The experimentally-determined values of the mass flow rates of secondary air and solids, .84 g/s and 2.4 g/s respectively, are less than 2 percent apart from their theoretical values. The stagnation pressure, however, was $P_{g1}=3.555$ bar which is more than twice (2.44 times) larger than its theoretical value of 1.455

Table 6.6. Mass Flow Rates, Temperatures, Nozzle Dimensions, and Pressures Measured During Test Using Modified Contour

Definition of Variable	Experimental Value	Theoretical Value	Percent Error
Stagnation Temperature of Primary Gas (T_{g1}) [°K]	296.3	296.0	.10
Stagnation Temperature of Secondary Gas (T_{g2}) [°K]	297.6	296.0	.54
Temperature of Solids (T_p) [°K]	296.0	296.0	.00
Stagnation Pressure of the Primary Air (P_{g1}) [bar]	3.555	1.455	144.3
Mass Flow Rate of Primary Air ($\dot{m}_{g1}$) [g/s]	50.7	48.30	4.9
Mass Flow Rate of Secondary Air ($\dot{m}_{g2}$) [g/s]	.84	.845	-.6
Mass Flow Rate of Solids ($\dot{m}_p$) [g/s]	2.4	2.415	-.6
Vertical Spacing Between Nozzle Blocks [mm]:			
B^*	9.00	19.60	-54.1
B_1	14.10	21.28	-33.7
B_2	21.00	21.54	-2.5
B_3	22.00	21.54	2.1
Static Pressures [bar]:			
P^*	2.302	.768	199.7
P_1	.444	.460	-3.5
P_2	.407	.460	-11.5
P_3	.921	.920	.1

bar. The experimental pressure ratio across the shock was $P_3/P_2=2.26$ instead of $P_3/P_2=2$.

Table H.3 contains the pressure readings along the channel. The experimentally-determined pressure distribution is shown in Figure 6.8 along with the pressure distribution for the frictionless flow model. Note the larger drop in static pressure through the converging-diverging nozzle for the flow with modified channel contour--an effect which was anticipated in Figure 6.7.

Table 6.7 shows the comparison between the cross-sectional areas of the modified contour and the cross-sectional areas given by the theoretical model. Note that the throat area had to be reduced to more than half its theoretical value. The experimental value of the cross-sectional area at section '1' was .638 times the theoretical value. On the other hand, A_2 and A_3 were kept within less than 3 percent from their respective theoretical values.

Figure 6.9 shows Schlieren pictures of the pseudo-shock for two flow conditions: (a) when no solids are injected through the injection tube and (b) when the solids mass flow rate is set to 2.4 g/s. Note that the addition of solids forces the pseudo-shock to move upstream from port 16 to a location midway between ports 14 and 15 (28 mm upstream from port 16). This effect occurs because as the solids are added to the flow in the injection tube, an additional amount of momentum is taken from the primary air to accelerate them. Any movement of the shock in an upstream direction will reduce the wall friction area of supersonic flow upstream of the shock and so the energy dissipation.

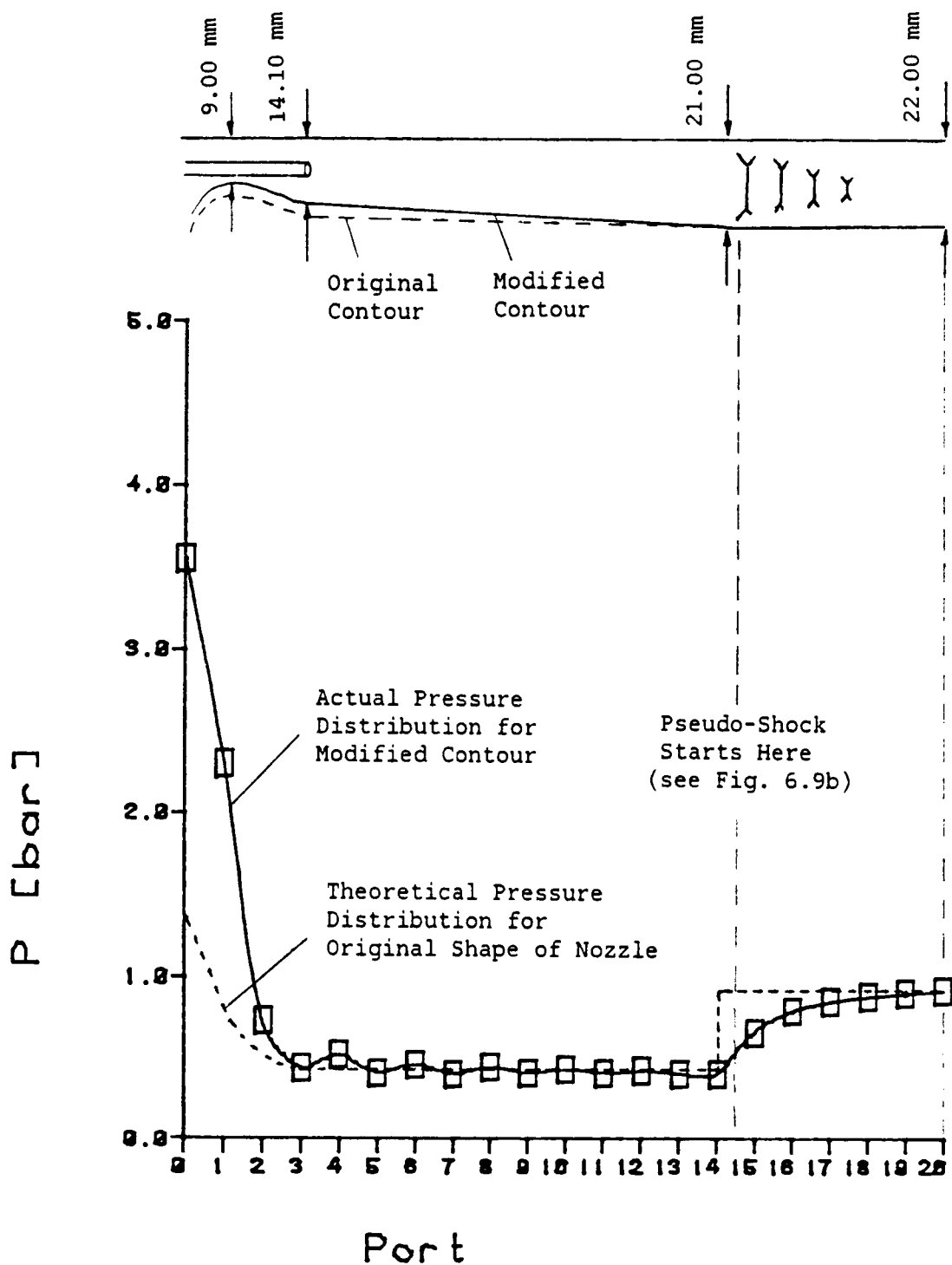


Figure 6.8. Pressure Distribution for Gas-Dynamic Injector Having a Modified Channel Contour with Theoretical Values of Mass Flow Rates and Stagnation Pressure of Primary Air

Table 6.7. Comparison between Theoretical and Modified Cross-Sectional Areas

Section:	*	1	2	3
Cross-Sectional Areas [mm ²]:				
Theoretical Results	141.35	157.24	170.95	170.95
Experimental Results	57.27	100.31	166.74	174.68
Ratio of Experimental-to-Theoretical Cross-Sectional Areas	.405	.638	.975	1.022

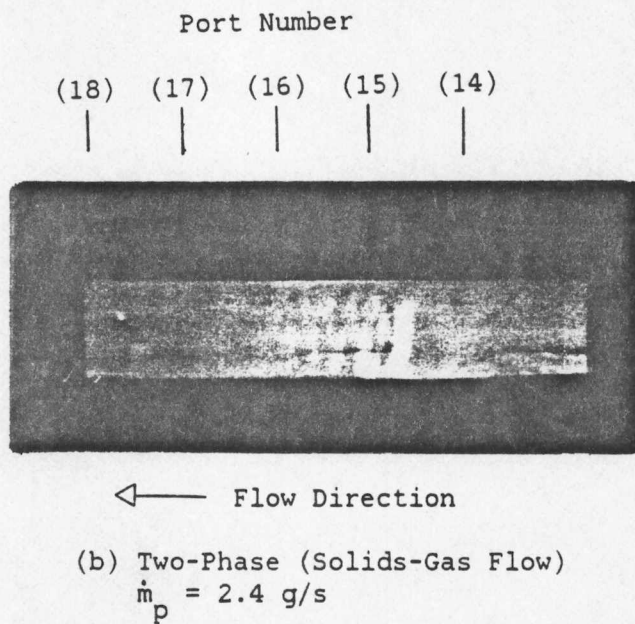
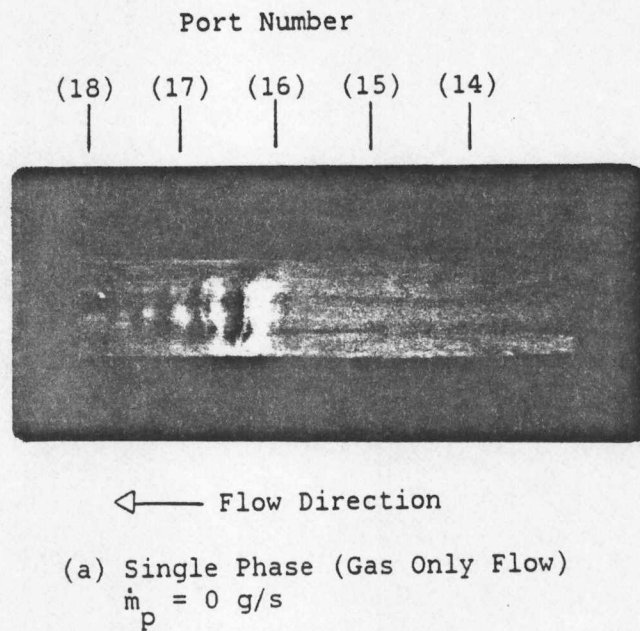


Figure 6.9. Schlieren Photographs of the Pseudo-Shock

(Note that the flow separates from the walls in the pseudo-shock region and, therefore, the friction at the walls along the pseudo-shock is negligible.) In addition, since the segment of the channel between ports 14 and 20 has a small amount of divergence, the total pressure drop across the shock decreases as the shock moves upstream to a section of smaller cross-sectional area.

Figure 6.10 shows a Schlieren picture of the region where the gas-solids suspension is injected. Note that the jet does not exit parallel to the injection tube axis. Instead, it deviates to a stable direction about 2 degrees from the horizontal towards the upper nozzle block. An oblique shock is attached to the injection tube at the exit section in the upper region and an expansion wave is attached to it at the exit section in the lower region. The existence of the oblique shock is verified by the experimental pressure readings of Table H.3. Note that the static pressure at the nozzle upper block increases from .444 bar at port 3 to .526 bar at port 4. Figure 6.11 shows the position of the pressure ports relative to the injection tube and the oblique shock, as well as the shock angles and deflection angles. The pressure P_e is not known; however, it can be estimated indirectly by knowing the pressure before the shock and the angles of the oblique shock and flow deflection (Appendix J). The result is $P_e = .494$ bar. This indicates that the actual exhaust-to-injection pressure ratio is $P_3/P_e = 1.86$ instead of $P_3/P_e = 2$ as originally planned. The pressure in region III was estimated using this result. Its value was $P(4)_{(est)} = .546$ bar which is slightly above the experimental value

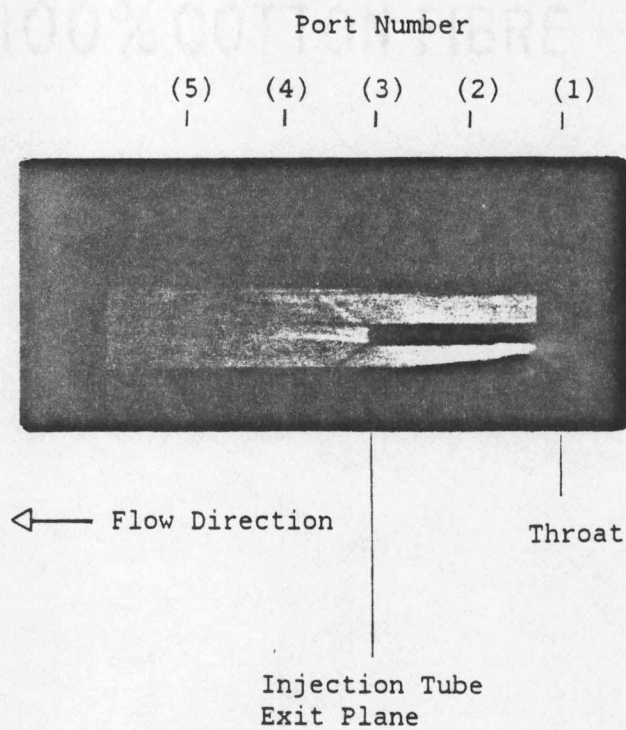


Figure 6.10. Schlieren Photograph of the Jet of Gas-Solids Suspension

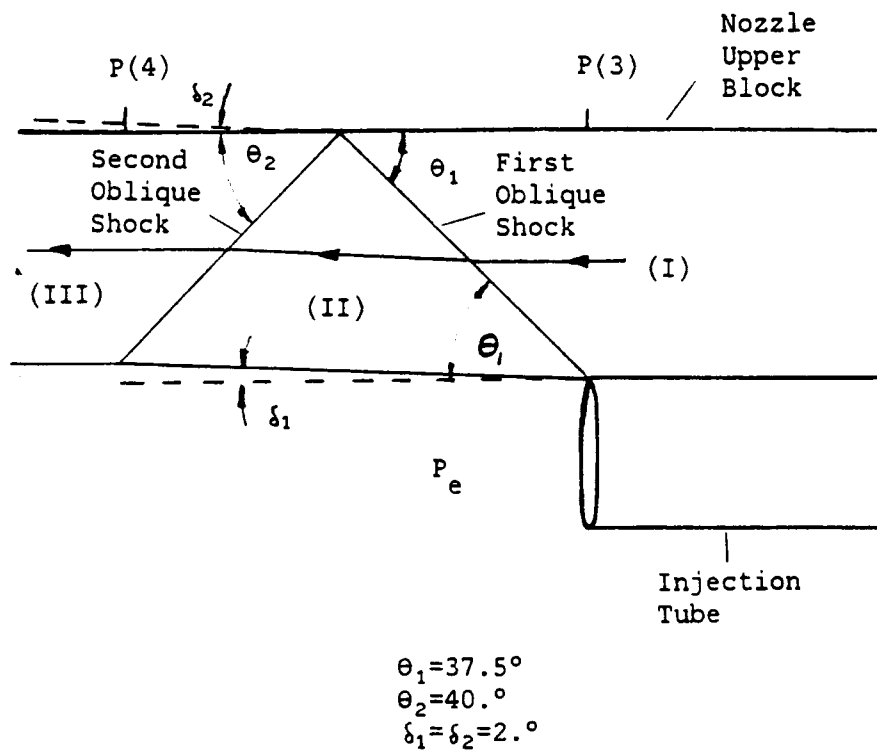


Figure 6.11. Geometric Characteristics of the Flow Field in the Region of Gas-Solids Jet Injection

($P(4)=.526$ bar). The estimated Mach number at section '1' (region I, Figure 6.11) was $M_{1(est)}=1.72$ which is greater than its theoretical value for frictionless flow $M_1=1.39$. This result was anticipated in Figure 6.6.

The results in this study suggest that the viscous effects have to be accounted for in the analytical model. This experiment shows, however, that there is a good agreement between the theoretical and experimental values of pressure ratio across the pseudo-shock when theoretical values of mass flow rates for all flows are used. Thus, the assumption of modeling the pseudo-shock as a single equivalent discontinuity (normal shock) is validated by the experimental results.

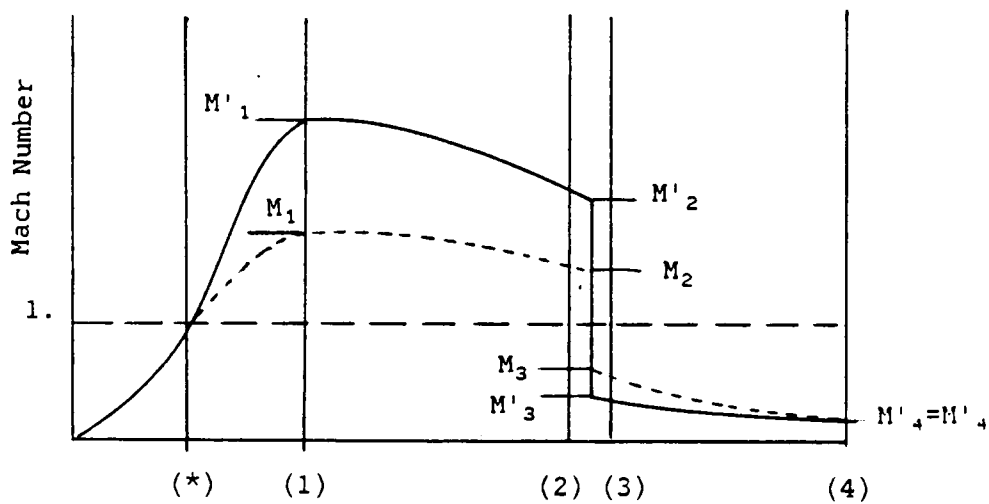
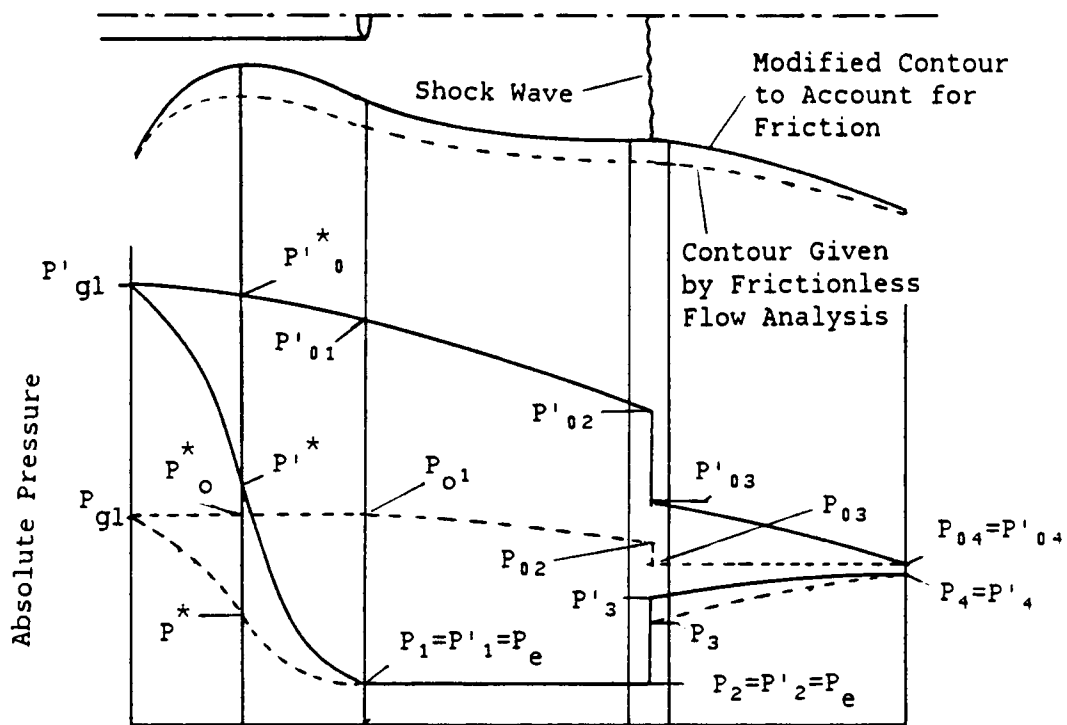
CHAPTER 7

SUGGESTED PROCEDURE FOR MODIFYING THE THEORETICAL RESULTS TO DESIGN AN ACTUAL GAS-DYNAMIC INJECTOR

In the experimental investigation it was found that, for an actual device constructed without a subsonic diffuser, the throat area as well as the flow area of the primary gas at the injection tube exit plane needed to be reduced with respect to their respective theoretical values and adjusted so that a constant-pressure mixing region could be established and the desired pressure ratio across the shock could be obtained. The following analysis is conducted to anticipate corrections to be made in the contour (cross-sectional areas) of a gas-dynamic injector designed with a subsonic diffuser and to qualitatively predict the static pressure, stagnation pressure and Mach number distributions.

Some restrictions are imposed in this analysis. The input and output flow conditions of the injector are assumed to be unchanged. Thus, the static pressure, stagnation pressure, total temperature, Mach numbers and cross-sectional areas at section 'e' and section '4' are kept at their design values given by frictionless flow calculations. It then follows that all mass flow rates are unchanged. It is assumed that the pseudo-shock process still can be modeled as a single normal shock.

Figure 7.1 shows qualitatively the GDI contour, the static pressure distribution, the stagnation pressure distribution, and the Mach number distribution given by the inviscid flow analysis. It also shows the expected contour and pressure and Mach number distributions for the actual device. Because the total pressure in a viscous flow with



Axial Position Along the Gas-Dynamic Injector

Figure 7.1. Comparison Between Theoretical and Actual Distributions of Cross-Sectional Areas, Pressures, and Mach Numbers in the Gas-Dynamic Injector

friction is lost along the injector, the stagnation pressure for the actual case (P'_{g1}) has to be increased above the value given by the inviscid flow analysis. The total pressure at the throat drops from P'_{g1} to P'^*_0 . Since the Mach number at the throat is always unity, it follows that the static pressure at the throat for the actual case (P'^*) has to be larger than its theoretical value (P^*). The equation of conservation of mass implies that the throat area has to be reduced below the theoretically-computed value so that the mass flow rate of the primary gas remains unchanged.

At section '1' the stagnation pressure is higher than the theoretical value ($P'_{01} > P_{01}$) while the static pressure remains at the design value (P_1). It follows that the Mach number at section '1' in the actual case is greater than theoretically predicted. An inspection of the continuity equation implies that the cross-sectional area at section '1' has to be smaller than the value given by frictionless analysis so that the mass flow rate remains fixed. (Note that the stagnation temperature of the primary gas has been fixed at its original value.) The actual total pressure at section '2' is again greater than the value theoretically predicted while the static pressure is fixed at the same value because of design conditions. Thus, according to the isentropic relations, the Mach number has to be greater in the actual case and the cross-sectional area has to be smaller ($M'_2 > M_2$ and $A'_2 < A_2$).

A stronger shock is expected in the actual device. Since the Mach number at section '2' (M'_2) is greater than the theoretical Mach number (M_2), the Mach number behind the shock (M'_3) has to be smaller than the value given by frictionless analysis (M_3) (according to normal shock

theory). Thus, a greater increase in the static pressure and a greater loss in the stagnation pressure is expected. The above implies that a smaller amount of static pressure recovery takes place in the subsonic diffuser for the actual conditions. Note that the stagnation pressure behind the shock needs to be higher than the stagnation pressure at section '4' to account for additional losses during the subsonic compression process along the diffuser.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Results from the analytical and experimental investigations suggest that practical applications of the gas-dynamic injector are feasible.

As seen in the parametric study, the mass flow rate of the secondary gas must be kept to a minimum in order to reduce the overall power consumption. The condition of minimum power requirements implies the existence of an optimum value for the mass flow rate of the primary gas. On the other hand, the condition of practical upper limits of pressure in the stagnation chamber imposes a restriction on the practical minimum value of the mass flow rate of the primary gas below which the gas-dynamic injector cannot operate. The pressure required in the stagnation chamber of the device is quite sensitive to changes in the inlet pressure (pressure in the injection tube). Thus, the pressure rise across the low-pressure differential solids feeder should be as high as possible so that the pressure in the stagnation chamber is within the practical limit on the maximum pressure. The ratio of stagnation temperature of the gas-solids suspension entering the device to the stagnation temperature of the primary gas should be as low as possible in order to reduce the required stagnation pressure of the primary gas.

The experimental investigation showed that viscous effects are too important to be neglected and that they should be taken into account for a more realistic analytical model. An improved analytical model should

also include the calculation of the mixing length, the calculation of the pseudo-shock, and the calculation of the relaxation length behind the pseudo-shock. These calculations can be made using numerical and/or empirical methods. The simplified analytical model presented in this project can be used, however, to assess the limits and the orders of magnitude of the design parameters, such as the stagnation pressure of primary gas and the cross-sectional areas of the device. The theoretical value of the stagnation pressure is a lower limit and the theoretical values of the cross-sectional areas are upper limits with the exception of the injection tube exit cross-sectional area and the GDI exit cross-sectional area.

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APPENDICES

APPENDIX A

COMPUTER PROGRAM USED IN THE PARAMETRIC STUDY

```

C      PROGRAM:      "GAS DYNAMIC INJECTOR" (GDI.FOR)
C      CREATED:      JAN. 8,1984
C      PURPOSE:      THIS PROGRAM COMPUTES THE FLOW PROPERTIES
C                    (PRESSURE, TEMPERATURE, MACH NO.) AND THE DUCT
C                    CROSS SECTIONAL AREAS FOR A FLOW OF GAS/SOLID
C                    SUSPENSION IN THE GAS DYNAMIC INJECTOR.
C
C      UPDATED:      FEB. 28,1985
C-----
C      INPUT FILE: FOR20.DAT
C      OUTPUT FILE: FOR40.DAT
C      FORMAT OF INPUT FILE:
C*****BEGINNING OF FILE FOR21.DAT*****
CGROUP SERIES  G      R      DP      CCP      ERROR
C XX      XX      XXX      XXX      XXX      XXX
CCASE DMP  NG1      NG2      TOE      TG1      PE      P4      ME M4
C1      XX      XX      XX      XX      XX      XX      XX      XX XX
C2      XX      XX      XX      XX      XX      XX      XX      XX XX
C.      .      .      .      .      .      .      .      . .
C.      .      .      .      .      .      .      .      . .
CN-1    .      .      .      .      .      .      .      . .
CN      XX      XX      XX      XX      XX      XX      XX      XX XX
C0      0      0      0      0      0      0      0      0 0
C*****END OF FILE*****
C
C      NOTE: GROUP AND SERIES ARE JUST FOR REFERENCES
C            DATA MAY BE WRITTEN WITHOUT DECIMAL POINT
C            HEADINGS AND SEPARATION LINES MUST BE INCLUDED
C
C      UNITS                                INPUT/OUTPUT  CALCULATIONS
C      AREAS..... [CM2]                    [M2]
C      LENGTHS..... [CM]                    [M]
C      PRESSURES..... [BAR]                  [PA]
C      TEMPERATURES..... [K]                  [K]
C      GAS CONSTANT (R)..... [N-M/KG-K]        [N-M/KG-K]
C      SPECIFIC HEAT ("CP" OR "C")..... [N-M/KG-K] [N-M/KG-K]
C      MASS FLOW RATE..... [KG/S]              [KG/S]
C-----
C      SECTION NO.      DESCRIPTION
C
C      S..... THROAT SECTION
C      1..... INJECTION TUBE EXIT PLANE
C      2..... BEGINNING OF NORMAL SHOCK
C      3..... END OF NORMAL SHOCK
C      4..... GDI EXIT SECTION
C-----
C      DESCRIPTION OF THE VARIABLES USED
C

```

C		FORTTRAN	MEANING
C		NAME	
C	AREAS:		
C		AS	THROAT AREA (A*) OR (ASTAR)
C		A1	AREA AT SECTION 1.
C		A2	" " " 2.
C		A3	" " " 3.
C		A4	" " " 4.
C		AE	INTERNAL AREA OF INJECTION TUBE
C			AT EXIT PLANE
C			
C	PRESSURES:		
C		PS	STATIC PRESSURE AT THE THROAT
C			(P*) OR (PSTAR)
C		P1	STATIC PRESSURE AT SECTION 1.
C		P2	" " " " 2.
C		P3	" " " " 3.
C		P4	" " " " 4.
C		PE	" " " THE INJECTION
C			TUBE EXIT PLANE
C			
C		P01	STAGNATION PRESSURE AT SECTION 1.
C		P02	" " " " 2.
C		P03	" " " " 3.
C		P04	" " " " 4.
C		POE	STAGNATION PRESSURE AT THE INJECTION
C			TUBE EXIT PLANE
C			
C	TEMPERATURES:		
C		TS	STATIC TEMPERATURE AT THE THROAT
C			(T*) OR (TSTAR)
C		T1	STATIC TEMPERATURE AT SECTION 1.
C		T2	" " " " 2.
C		T3	" " " " 3.
C		T4	" " " " 4.
C		TE	" " " THE INJECTION
C			TUBE EXIT PLANE
C		TP	SOLIDS TEMPERATURE
C			
C		T01	STAGNATION TEMPERATURE AT SECTION 1.
C		T02	" " " " 2.
C		T03	" " " " 3.
C		T04	" " " " 4.
C		T0E	STAGNATION TEMPERATURE AT THE INJECTION
C			TUBE EXIT PLANE
C		TG1	STAGNATION TEMPERATURE OF PRIMARY
C			GAS AT STAGNATION CHAMBER
C			
C	MACH NO.:		
C		MS	MACH NO. AT THE THROAT (M*) OR (MSTAR)
C		M1	" " " SECTION 1.

C	M2	"	"	"	"	2.
C	M3	"	"	"	"	3.
C	M4	"	"	"	"	4.
C	ME	"	"	"	THE INJECTION TUBE	
C		EXIT PLANE				
C	M2MIN	MINIMUM MACH NUMBER THAT ALLOWS				
C		A DISPERSE SHOCK				
C	M2MAX	MAXIMUM MACH NUMBER				
C	MASS FLOW					
C	RATES:					
C	DMP	PARTICLE MASS FLOW RATE				
C	DMG1	PRIMARY GAS MASS FLOW RATE				
C	DMG2	SECONDARY GAS MASS FLOW RATE				
C	DME	MASS FLOW RATE OF MIXTURE INSIDE				
C		INJECTION TUBE				
C	DMT	TOTAL MASS FLOW RATE				
C	OTHER					
C	PARAMETERS:					
C	G	GAS SPECIFIC HEAT RATIO ($G=GAMMA=CP/CV$)				
C	R	GAS CONSTANT ($R=CP-CV$)				
C	C	SOLIDS SPECIFIC HEAT				
C	CP	GAS CONSTANT PRESSURE SPECIFIC HEAT				
C	CV	GAS CONSTANT VOLUME SPECIFIC HEAT				
C	GE	SPECIFIC HEAT RATIO FOR THE GAS/SOLID				
C		SUSPENSION AT THE INJECTION TUBE EXIT				
C		PLANE				
C	GM	SPECIFIC HEAT RATIO FOR THE MIXTURE				
C		OF THE MAIN CARRIER GAS AND THE				
C		GAS/SOLID SUSPENSION FROM THE				
C		INJECTION TUBE				
C	RE	MODIFIED GAS CONSTANT FOR THE GAS/SOLID				
C		SUSPENSION IN THE INJECTION TUBE				
C	RM	MODIFIED GAS CONSTANT FOR THE MIXTURE				
C		OF THE MAIN CARRIER GAS AND THE				
C		GAS/SOLID SUSPENSION FROM THE				
C		INJECTION TUBE				
C	CPE	MODIFIED CONSTANT PRESSURE SPECIFIC				
C		HEAT FOR GAS/SOLID SUSPENSION				
C		IN THE INJECTION TUBE				
C	CPM	MODIFIED CONSTANT PRESSURE SPECIFIC				
C		HEAT FOR THE MIXTURE OF MAIN				
C		CARRIER GAS AND GAS/SOLID SUSPENSION				
C		FROM THE INJECTION TUBE				
C	CCP	C/CP				
C	CPEC	CPE/CP				

C	CPMCP	CPM/CP
C	RER	RE/R
C	RMR	RM/R
C		
C	DP	DENSITY OF PARTICLES
C		
C	SVF	SOLIDS VOLUME FRACTION
C		
C	NG1	RATIO OF MASS FLOW RATES OF MAIN CARRIER GAS TO MASS FLOW RATE OF SOLIDS (DMG1/DMP).
C		
C	NG2	RATIO OF MASS FLOW RATES OF SECONDARY GAS TO MASS FLOW RATE OF SOLIDS (DMG2/DMP).
C		
C		DMP SOLIDS MASS FLOW RATE (D(MP)/DT)
C		
C	FF	VARIABLE TO BE RELAXED TO ZERO FF=P4P1IT-PAP1
C		
C	ERROR	ERROR USED IN ITERATION TO HALT PROCESS <ABS(FF/P4PE) MUST BE LESS THAN ERROR FOR THE ITERATION TO BE STOPPED>
C		
C	AREA RATIOS:	
C	ASA1	AS/A1
C	A1A1	A1/A1
C	A2A1	A2/A1
C	A3A1	A3/A1
C	A4A1	A4/A1
C	AEA1	AE/A1
C		
C	PRESSURE	
C	RATIOS:	
C	PSPG1	PS/PG1
C	P1PG1	P1/PG1
C	P2PG1	P2/PG1
C	P3PG1	P3/PG1
C	P4PG1	P4/PG1
C	PEPG1	PE/PG1
C	PG1PG1	PG1/PG1
C	P04PG1	P04/PG1 (=P03/PG1)
C	P0EPG1	P0E/PG1
C		
C	PSP4	PS/P4
C	P1P4	P1/P4
C	P2P4	P2/P4
C	P3P4	P3/P4
C	P4P4	P4/P4

```

C
C          POEP1          POE/P1
C          P01P1          P01/P1
C          P01PS          P01/PS
C          P02P2          P02/P2
C          P03P3          P03/P3
C          P04P4          P04/P4
C          POEPE          POE/PE
C          P4PE           P4/PE
C          P4PEMI         (P4/PE)MINIMUM
C          P4PEMA         (P4/PE)MAXIMUM
C          P4PEIT         VALUE OF (P4/PE) CALCULATED USING THE
C                          VALUE OF (M2) OBTAINED BY THE
C                          ITERATION PROCESS
C
C      TEMPERATURE
C      RATIOS:
C          TSTG1          TS/TG1
C          T1TG1          T1/TG1
C          T2TG1          T2/TG1
C          T3TG1          T3/TG1
C          T4TG1          T4/TG1
C          TG1TG1         TG1/TG1
C          T04TG1         T04/TG1 (=T02/TG1=T03/TG1)
C          T0ETG1         T0E/TG1
C
C          T01TS          T01/TS
C          T01T1          T01/T1
C          T0ETE          T0E/TE
C          T02T2          T02/T2
C          T03T3          T03/T3
C          T04T4          T04/T4
C
C
C          REAL MS,M1,M2,M3,M4,ME,M2MIN,M2MAX,M2T,NG1,NG2,M2A,M2B
C          INTEGER CASE,GROUP,SERIES
C          READ(20,888)HEADNG
888      FORMAT(A)
C          READ(20,*)GROUP,SERIES,G,R,DP,CCP,ERROR
C      SKIP HEADING LINE IN DATA FILE
C          READ(20,999)HEADNG
999      FORMAT(A)
C      READ IN DATA.
100     READ(20,*,END=500) CASE,DMP,NG1,NG2,T0E,TG1,PE,P4,ME,M4
C      THE FOLLOWING INSTRUCTION HALTS THE PROGRAM EXECUTION IF A ZERO (0)
C      IS ENCOUNTERED AT THE BEGINNING OF A LINE IN THE DATA FILE.
C          IF(CASE.EQ.0)GOTO 500
C      READ OUT DATA.
C          WRITE(40,2) GROUP,SERIES,CASE,G,R,DP,CCP,DMP,NG1,NG2,
C          $ T0E,TG1,PE,P4,ME,M4,ERROR
C

```

```

C   CONVERSION OF PRESSURE BAR TO PA
      PE=PE*1.E5
      P4=P4*1.E5
C
C   COMPUTE FLUID PROPERTIES.
      RE= R*NG2/(NG2+1)
      GE=G*(NG2+(CCP))/(NG2+G*(CCP))
      CPEC= (NG2+(CCP))/(NG2+1)
      RER=RE/R
      RM=R*(NG1+NG2)/(NG1+NG2+1)
      GM=G*(NG1+NG2+(CCP))/(NG1+NG2+G*(CCP))
      CPMCP=(NG1+NG2+(CCP))/(NG1+NG2+1)
      RMR=RM/R
      WRITE(40,3)GROUP,SERIES,CASE
      WRITE(40,4)GE,RER,CPEC,GM,RMR,CPMCP
C   VERIFY IF THE FLOW IS POSSIBLE.
C   I. COMPUTE THE MINIMUM MACH NO. WHICH ALLOWS THE FORMATION OF
C       A DISCONTINUOUS SHOCK.
      M2MIN=SQRT(G/GM/RMR)
C   II. COMPUTE THE MINIMUM PRESSURE RATIO WHICH ALLOWS THE FORMATION
C       OF A DISCONTINUOUS SHOCK.
      P4PEMI=((((GM+1.)/2.*M2MIN**2)/(1.+(GM-1.)/2.*M4**2)))**
      $ (GM/(GM-1))
      $ *(2.*GM*M2MIN**2/(GM+1.)-(GM-1.)/(GM+1.))**((1./(1.-GM))
C   III. COMPUTE THE ACTUAL PRESSURE RATIO (P4/PE).
      P4PE=P4/PE
      WRITE(40,6)M2MIN,P4PEMI,P4PE
C   IV. COMPARE THE ACTUAL PRESSURE RATIO (P4PE) WITH THE MINIMUM
C       PRESSURE RATIO (P4PEMI). IF (P4PE) IS GREATER THAN (P4PEMI)
C       CONTINUE CALCULATIONS; OTHERWISE, WRITE A MESSAGE AND
C       START WITH A NEW CASE.
      IF(P4PE.GT.P4PEMI) GOTO 200
      WRITE(40,8)
      GOTO 100
C   V. CHECK IF P4PE IS GREATER THAN THE P4PEMA.
200  T02=(TG1*NG1+CPEC*TOE*(NG2+1))/(CPMCP*(NG1+NG2+1))
      M2MAX= ( GM*RM*T02 /((NG1*SQRT(2*G*R*TG1/(G-1)) +
      $ (NG2+1)*SQRT(GE*RE*TOE/(1./ME**2+(GE-1)/2.)))/(1.+NG1+NG2))**2
      $ - (GM-1.)/2 ) ** -.5
      P4PEMA=((((GM+1.)/2.*M2MAX**2)/(1.+(GM-1.)/2.*M4**2)))**((GM/(GM-1))
      $ *(2.*GM*M2MAX**2/(GM+1.)-(GM-1.)/(GM+1.))**((1./(1.-GM))
      WRITE(40,7)M2MAX,P4PEMA,P4PE
      IF(P4PE.LT.P4PEMA) GOTO 210
      WRITE(40,9)
      GOTO 100
C   NEXT, COMPUTE THE VARIABLES IN THE SET OF EQUATIONS THAT CAN
C       BE SOLVED DIRECTLY WITH THE DATA AVAILABLE.
210  P1=PE
      P2=PE
      T0S=TG1
      T01=TG1

```

```

TOSTS=(G+1.)/2.
TS=TOS/TOSTS
TOETE=1.+(GE-1.)/2.*ME**2
TE=TOE/TOETE
POEPE=TOETE**(GE/(GE-1.))
POE=POEPE*PE
T02=(T01*NG1+CPECP*T0E*(NG2+1))/(CPMCP*(NG1+NG2+1))
T03=T02
T04=T03
T04T4=1.+(GM-1.)/2*M4**2
T4=T04/T04T4
P04P4=T04T4**(GM/(GM-1.))
P04=P04P4*P4
P03=P04
AE=DMP*(NG2+1)/PE/ME*SQRT(RE*TE/GE)
A4=DMP*(NG1+NG2+1)/P4/M4*SQRT(RM*T4/GM)
C
C  COMPUTATION OF M2 -- ITERATION PROCESS
C    INITIALIZE ITERATION PARAMETERS.
C
M2=M2MIN
290  M2=M2+1
      FF=FNCT(M2,M4,P4PE,GM)
      IF (FF.LE.0.) GOTO 290
C
C  BEGINNING OF ITERATION PROCESS
      M2A=M2-1
      M2B=M2
310  M2=(M2A+M2B)/2
      FF=FNCT(M2,M4,P4PE,GM)
      IF (ABS(FF/P4PE).LT.ERROR) GOTO 400
      IF (FF.GT.0.) GOTO 320
      M2A=M2
      GOTO 310
320  M2B=M2
      GOTO 310
400  P4PEIT=FF+P4PE
      WRITE(40,10) P4PEIT
C  END OF ITERATION PROCESS
C  COMPUTE THE REST OF THE VARIABLES.
      M3=((M2**2+2.)/(GM-1.))/(2.*GM*M2**2/(GM-1.))-1.))**.5
      T02T2=1.+(GM-1.)/2.*M2**2
      T2=T02/T02T2
      P02P2=T02T2**(GM/(GM-1.))
      P02=P02P2*P2
      T03T3=1.+(GM-1.)/2.*M3**2
      T3=T03/T03T3
      P03P3=T03T3**(GM/(GM-1.))
      P3=P03/P03P3
      A2=DMP*(NG1+NG2+1)/P2/M2*SQRT(RM*T2/GM)
      A3=A2

```

```

      PHI=(( (NG1+NG2+1)*M2*SQRT(GM*RM*T2)-(NG2+1)*ME*
$  SQRT(GE*RE*TE))/NG1)**2/G/R/T01
      M1=1./SQRT(1./PHI-(G-1.)/2.)
      T01T1=1.+(G-1.)/2.*M1**2
      T1=T01/T01T1
      P01P1=T01T1**(G/(G-1.))
      P01=P01P1*P1
      POS=P01
      PG1=POS
      POSPS=TOSTS**(G/(G-1.))
      PS=POS/POSPS
      AS=DMP*NG1/PS*SQRT(R*TS/G)
      A1=DMP*NG1/P1/M1*SQRT(R*T1/G)
C
C   AT THIS POINT THE SET OF EQUATIONS IS SOLVED.
C
C   ESTIMATE THE SOLDS VOLUME FRACTION FOR SECTIONS 'E' AND '4'
C   NOTE: THIS IS ONLY AN ESTIMATE SINCE THE ASSUMPTION
C   SVF=0 FOR THE DERIVATION OF EQUATIONS IMPLIES THAT
C   P,T,M, AND A ARE NOT EXACT EVEN FOR AN EXACT NON-NUMERICAL
C   SOLUTION. IN ADDITION THE EXPRESSION TO BE USED FOR SVF
C   IS ALSO AN APPROXIMATION.
      SVFE=PE/DP/R/TE/NG2
      SVF4=P4/DP/R/T4/(NG1+NG2)
C
C   CONVERSION OF AREAS : SQ. M TO SQ. CM
      AS=AS*1.E4
      A1=A1*1.E4
      A2=A2*1.E4
      A3=A3*1.E4
      A4=A4*1.E4
      AE=AE*1.E4
C
C   CONVERSION OF PRESSURE : PA TO BAR
      PS=PS*1.E-5
      P1=P1*1.E-5
      P2=P2*1.E-5
      P3=P3*1.E-5
      P4=P4*1.E-5
      PE=PE*1.E-5
      PG1=PG1*1.E-5
C
      POS=POS*1.E-5
      P01=P01*1.E-5
      P02=P02*1.E-5
      P03=P03*1.E-5
      P04=P04*1.E-5
      POE=POE*1.E-5
C
C   ADDITIONAL COMPUTATIONS
      ASAE=AS/AE

```

```

A1AE=A1/AE
A2AE=A2/AE
A3AE=A3/AE
A4AE=A4/AE
C
PG1P4=PG1/P4
PSP4=PS/P4
P1P4=P1/P4
P2P4=P2/P4
P3P4=P3/P4
P4P4=1
PEP4=PE/P4
C
PSPG1=PS/PG1
P1PG1=P1/PG1
P2PG1=P2/PG1
P3PG1=P3/PG1
P4PG1=P4/PG1
PEPG1=PE/PG1
PG1PG1=1
C
POSPG1=1
P01PG1=1
P02PG1=P02/PG1
P03PG1=P03/PG1
P04PG1=P04/PG1
POEPG1=P0E/PG1
C
TSTG1=TS/TG1
T1TG1=T1/TG1
T2TG1=T2/TG1
T3TG1=T3/TG1
T4TG1=T4/TG1
TETG1=TE/TG1
TG1TG1=1
C
T0STG1=1
T01TG1=1
T02TG1=T02/TG1
T03TG1=T03/TG1
T04TG1=T04/TG1
T0ETG1=T0E/TG1
C
C
MS=1.
C
WRITE(40,12)
WRITE(40,14)AS,A1,A2,A3,A4,ASAE,A1AE,A2AE,A3AE,A4AE
WRITE(40,16)MS,M1,M2,M3,M4
C
WRITE(40,18)PG1,PS,P1,P2,P3,P4

```

```

WRITE(40,20)PG1PG1,PSPG1,P1PG1,P2PG1,P3PG1,P4PG1
WRITE(40,22)PG1,POS,P01,P02,P03,P04
WRITE(40,24)PG1PG1,POSPG1,P01PG1,P02PG1,P03PG1,P04PG1
WRITE(40,25)PG1P4,PSP4,P1P4,P2P4,P3P4,P4P4
C
WRITE(40,26)TG1,TS,T1,T2,T3,T4
WRITE(40,28)TG1TG1,TSTG1,T1TG1,T2TG1,T3TG1,T4TG1
WRITE(40,30)TG1,T0S,T01,T02,T03,T04
WRITE(40,32)TG1TG1,T0STG1,T01TG1,T02TG1,T03TG1,T04TG1
C
WRITE(40,34)AE,ME,POE,PE,TOE,TE
WRITE(40,36)SVFE,SVF4
GOTO 100
500 WRITE(5,*)' RESULTS ARE IN FILE: FOR40.DAT'
STOP
C
2 FORMAT('1',T2,'GROUP:',I2,5X,'SERIES:',I2,5X,'CASE:',I2
$ /T12,'-LOAD DATA-'/
$ /T12,'G=',F10.4
$ /T12,'R=',F10.4,' N-M/KG-K'
$ /T11,'DP=',F10.4,' KG/M3'
$ /T9,'C/CP=',F10.4
$ /
$ /T10,'DMP=',F10.3,' KG/S'
$ /T10,'NG1=',F10.3
$ /T10,'NG2=',F10.3
$ /T10,'TOE=',F10.2,' K'
$ /T10,'TG1=',F10.2,' K'
$ /T11,'PE=',F10.3,' BAR'
$ /T11,'P4=',F10.3,' BAR'
$ /T11,'ME=',F10.5
$ /T11,'M4=',F10.5
$ /T10,' ITERATION PRESSURE RATIO ERROR=',G10.5
$ )
3 FORMAT('1',T2,'GROUP:',I2,5X,'SERIES:',I2,5X,'CASE:',I2
$ /T12,'-RESULTS-'/)
4 FORMAT(T6,'FLUID PROPERTIES'/T6,'GE=',F8.5,T21,'RE/R=',
$ F8.5,T39,'CPE/CP=',F8.5/T6,'GM=',F8.5,T21,'RM/R=',
$ F8.5,T39,'CPM/CP=',F8.5)
6 FORMAT(/T17,'M2MIN=',F8.5/T12,'(P4/PE)MIN=',F8.4/T17,'P4/PE=',
$ F8.4)
7 FORMAT(/T17,'M2MAX=',F8.5/T12,'(P4/PE)MAX=',F8.4/T17,'P4/PE=',
$ F8.4)
8 FORMAT(T2,'THIS FLOW IS NOT POSSIBLE (P4PE < P4PEMIN) ')
9 FORMAT(T2,'THIS FLOW IS NOT POSSIBLE (P4PE > P4PEMAX) ')
10 FORMAT(T6,'(P4/PE)ITERATION=',F8.4)
12 FORMAT(/T8,'SECTION:',4X,'01',6X,'THROAT',7X,'1',9X,'2',9X,
$ '3',9X,'4'/)
14 FORMAT(T3,'A [SQ.CM]',T25,5(1X,F9.2)
$ /T3,'A/AE',T25,5(1X,F9.3)/)
16 FORMAT(T3,'MACH NO.',T25,5(2X,F8.5)/)

```

```

18     FORMAT(T3,'P [BAR]',T15,6(1X,F9.2)///)
20     FORMAT(T3,'P/PG1',T15,6(1X,F9.5)///)
22     FORMAT(T3,'P(TOTAL)[BAR]',T15,6(1X,F9.2)///)
24     FORMAT(T3,'P0/PG1',T15,6(1X,F9.5)///)
25     FORMAT(T3,'P/P4 ',T15,6(1X,F9.3)///)
26     FORMAT(T3,'T [K]',T15,6(1X,F9.2)///)
28     FORMAT(T3,'T/TG1',T15,6(1X,F9.5)///)
30     FORMAT(T3,'T(TOTAL) [K]',T15,6(1X,F9.2)///)
32     FORMAT(T3,'T0/TG1',T15,6(1X,F9.5)///)
34     FORMAT(T16,'INJECTION TUBE'/T11,'AE=',F8.2,' SQ.CM'/
$ T11,'ME=',F9.5/T11,'POE=',F8.2,' BAR',4X,'PE=',F8.2,' BAR'/
$ T11,'TOE=',F8.2,' K '4X,'TE=',F8.2,' K '/)
36     FORMAT(T11,'SOLIDS VOLUME FRACTION',
$/T11,'SVFE=',E10.2/T11,'SVF4=',E10.2)
      END

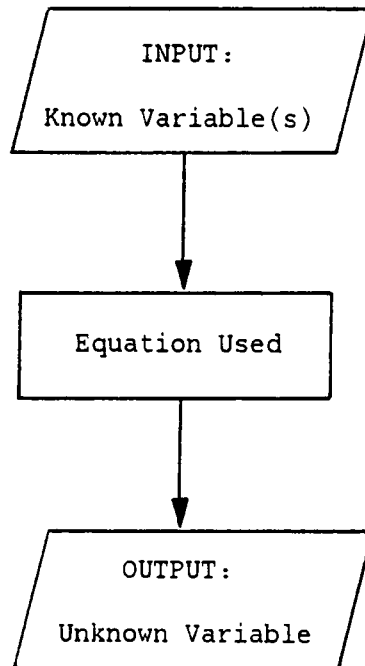
C
      FUNCTION FNCT(M2,M4,P4PE,GM)
      REAL M2,M4
      FF=(( (GM+1.)/2.*M2**2)/(1.+(GM-1.)/2.*M4**2))** (GM/(GM-1.))*
$ (2.*GM*M2**2/(GM+1.)-(GM-1.)/(GM+1.))** (1./(1.-GM))-P4PE
      FNCT=FF
      RETURN
      END

```

APPENDIX B

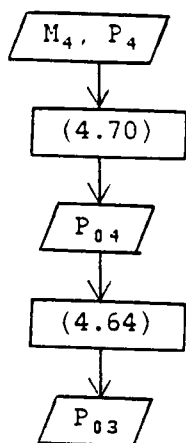
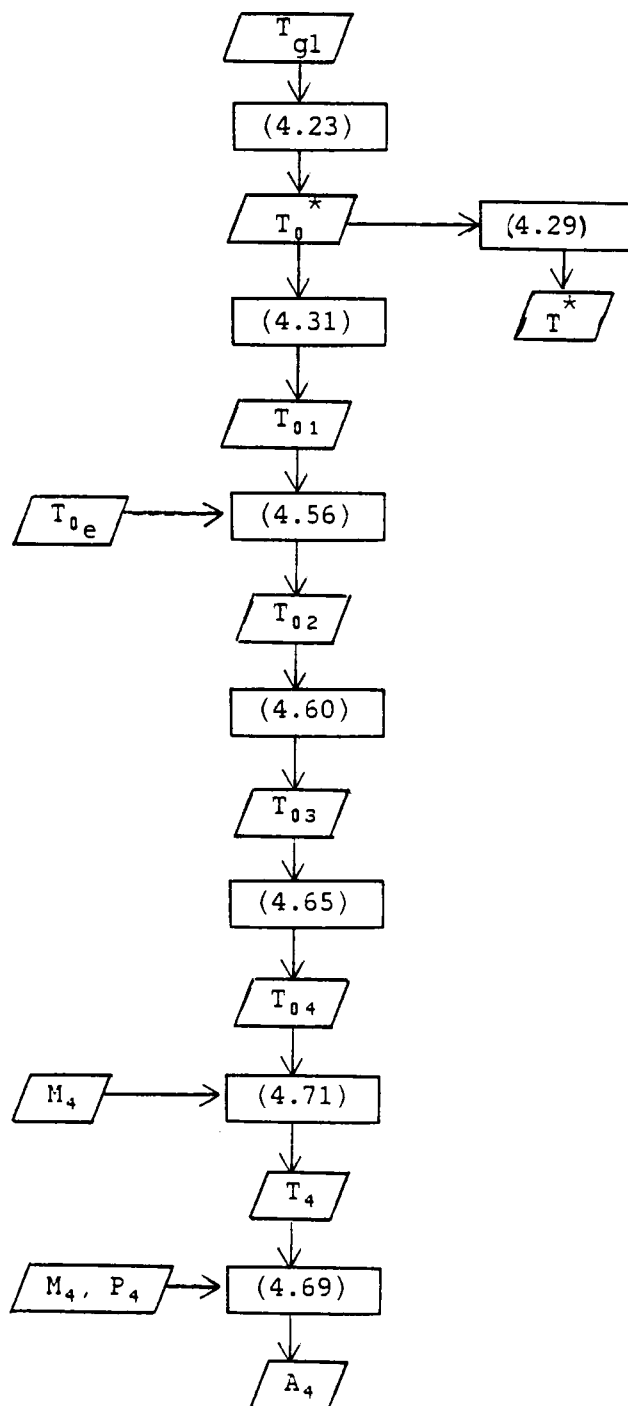
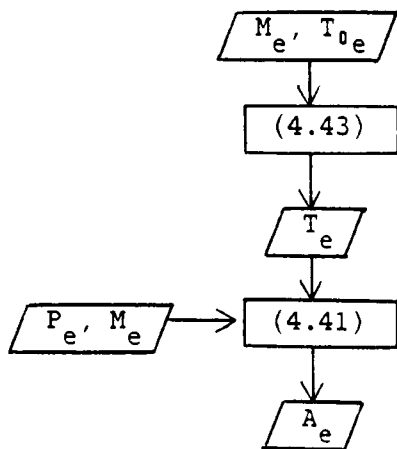
FLOW DIAGRAM FOR PROGRAM GDI

The flow diagram shows the sequence of the equations to be used in order to solve for all unknowns. The numbers of the equations are shown instead of the equations themselves for simplicity. The way to read the flow diagram is as follows:

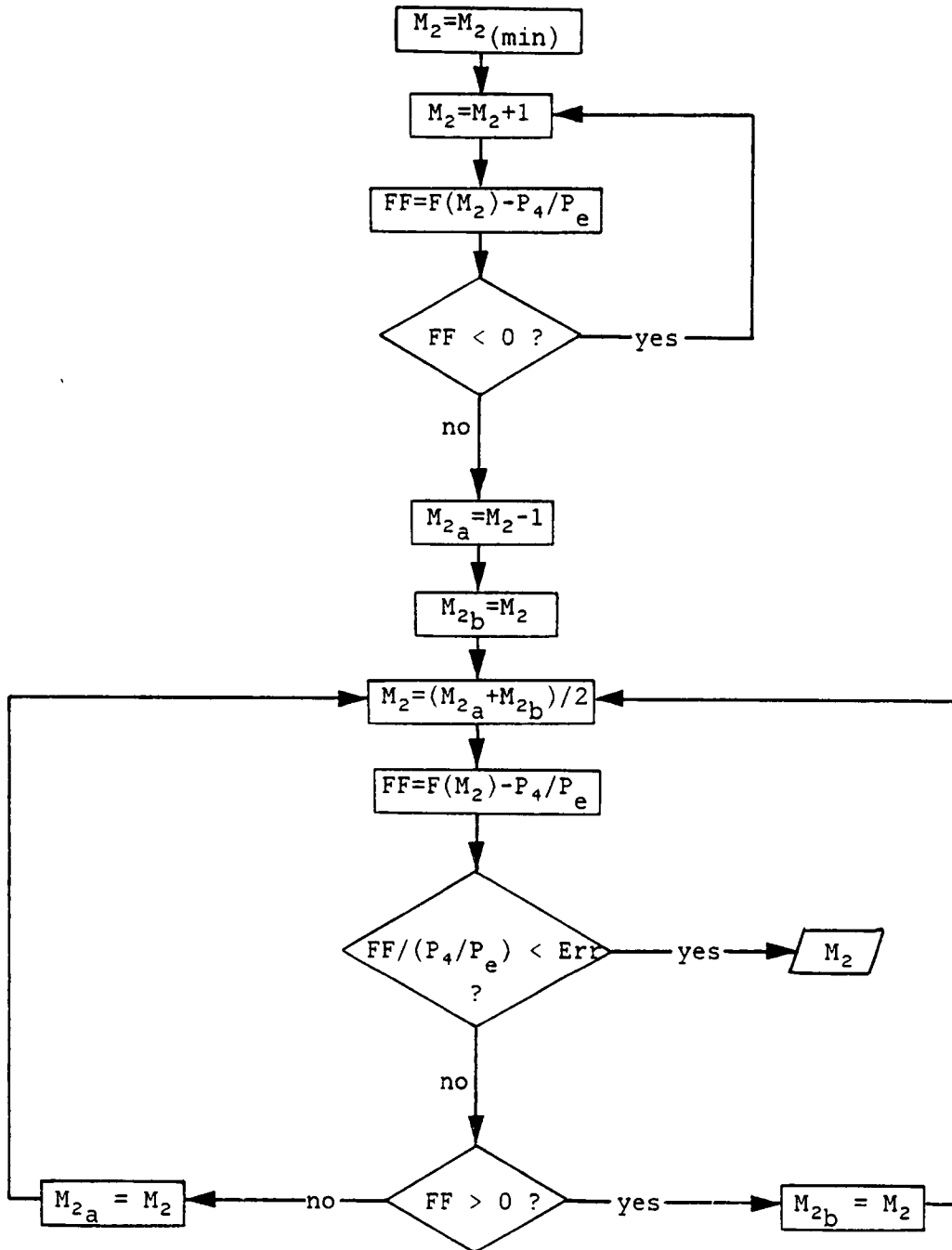


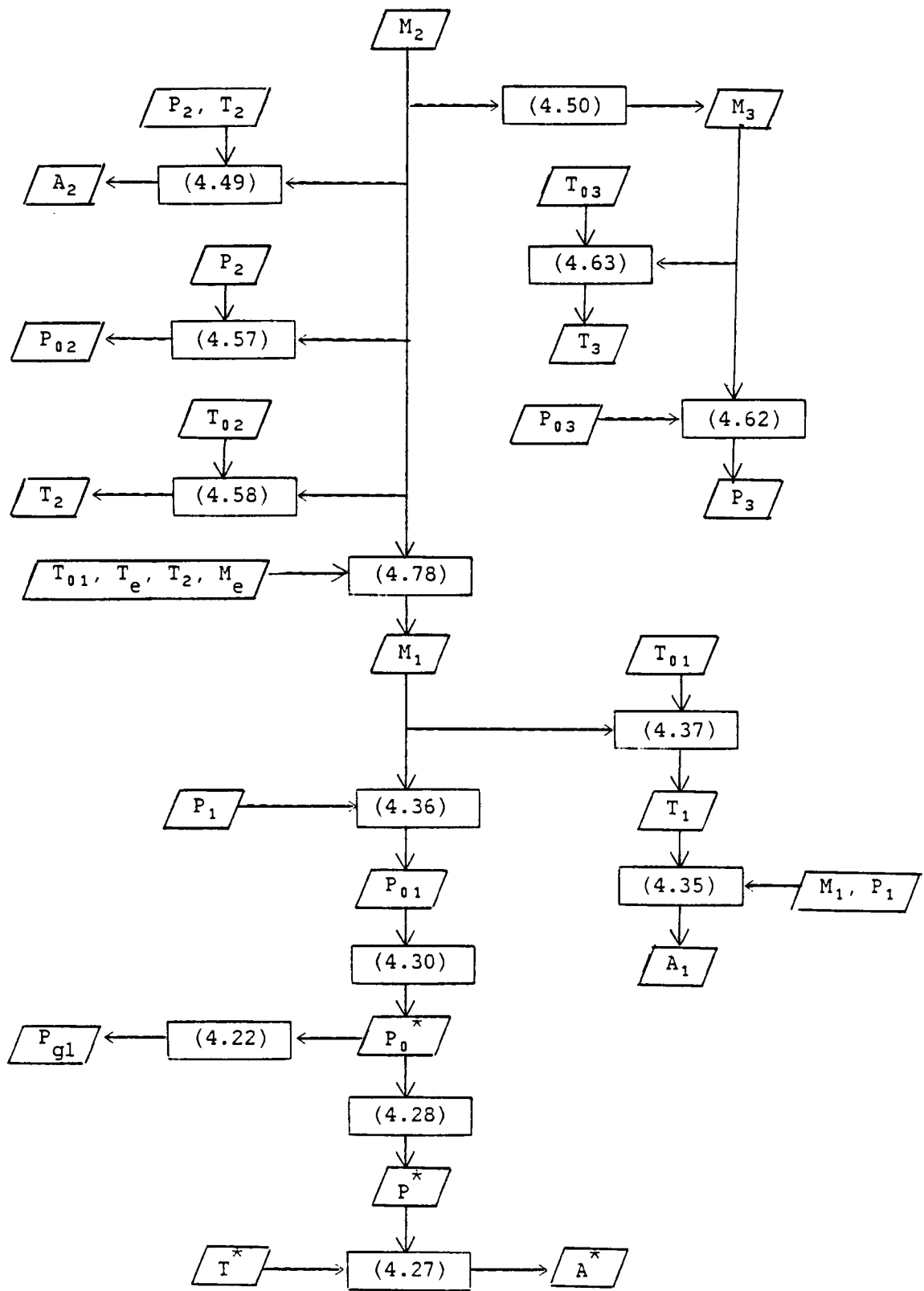
Note:

The flow properties R_e , γ_e , c_{pe}/c_p , R_m , γ_m , and c_{pm}/c_p are computed first and are considered constant parameters for subsequent calculations.



At this point all unknowns independent of M_2 are determined. In order to solve for the rest of the unknowns M_2 has to be determined. This is done by the half-interval-search iteration illustrated below.





APPENDIX C

NUMERICAL RESULTS OF THE PARAMETRIC STUDY

Table C.1. Pressure Ratio P_{g1}/P_4 as a Function of the Primary and Secondary Air Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
6	9855.13	1025368.36	--	--	--
8	231.78	468.87	1317.12	6398.56	170345.60
10	73.46	107.38	175.61	322.52	691.51
12	40.79	52.86	72.93	106.14	163.84
14	28.13	34.22	43.41	56.85	76.85
16	21.84	25.55	31.19	38.52	48.56
18	18.32	20.91	24.45	29.06	35.04
20	15.92	17.83	20.37	23.58	27.59
40	9.11	9.54	10.07	10.66	11.32
60	7.70	7.92	8.20	8.49	8.81
80	7.10	7.25	7.43	7.62	7.83
100	6.77	6.88	7.02	7.16	7.31
120	6.56	6.65	6.76	6.87	6.99
140	6.42	6.49	6.58	6.67	6.77
160	6.31	6.38	6.45	6.53	6.61
180	6.23	6.29	6.35	6.42	6.49
∞	5.635	5.635	5.635	5.635	5.635

Table C.2. Maximum Value of P_4/P_e ($[P_4/P_e]_{(max)}$) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
0	1.665	1.686	1.702	1.716	1.728
2	8.42	7.82	7.23	6.72	6.28
4	14.24	13.20	12.20	11.32	10.55
6	19.93	18.46	17.05	15.80	14.71
8	25.59	23.67	21.85	20.24	18.83
10	31.24	28.87	26.64	24.66	22.93
12	36.88	34.06	31.41	29.07	27.02
14	42.51	39.24	36.18	33.47	31.11
16	48.14	44.42	40.94	37.87	35.19
18	53.76	49.60	45.70	42.27	39.27
20	59.39	54.78	50.46	46.66	43.34
30	87.49	80.64	74.24	68.61	63.70
40	115.59	106.49	98.01	90.54	84.04
50	143.69	132.33	121.77	112.47	104.37
60	171.78	158.18	145.52	134.40	124.71
80	227.97	209.86	193.03	178.25	165.37
100	284.15	261.54	240.54	222.09	206.02
120	340.33	313.22	288.05	265.93	246.68
140	396.50	364.89	335.55	309.78	287.33
160	452.68	416.57	383.06	353.62	327.98
180	508.86	468.25	430.57	397.46	368.63

Table C.3. Minimum Value of P_4/P_e ($[P_4/P_e]_{(min)}$) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
0	8.781	5.303	4.174	3.570	3.225
2	2.478	2.426	2.383	2.346	2.314
4	2.187	2.173	2.160	2.148	2.137
6	2.086	2.079	2.073	2.067	2.062
8	2.034	2.031	2.027	2.024	2.020
10	2.004	2.001	1.999	1.997	1.994
12	1.983	1.981	1.980	1.978	1.976
14	1.968	1.967	1.966	1.964	1.963
15	1.962	1.961	1.960	1.959	1.958
16	1.957	1.956	1.955	1.954	1.953
18	1.948	1.948	1.947	1.946	1.946
20	1.942	1.941	1.940	1.940	1.939
30	1.921	1.921	1.920	1.920	1.920
40	1.911	1.911	1.911	1.910	1.910
50	1.904	1.904	1.904	1.904	1.904
60	1.900	1.900	1.900	1.900	1.900
80	1.895	1.895	1.895	1.895	1.895
100	1.892	1.892	1.892	1.892	1.892
120	1.890	1.890	1.890	1.890	1.890
140	1.889	1.889	1.889	1.889	1.889
160	1.887	1.887	1.887	1.887	1.887
180	1.887	1.887	1.887	1.887	1.887

Table C.4. Injection Tube Exit Area (A_e) as a Function of the Parameter N_{g2}

A_e [cm ²]	N_{g2}				
	.2	.4	.6	.8	1.
	21.30	31.77	40.80	49.18	57.18

Table C.5. Ratio of Throat Cross-Sectional Area to Injection Tube Exit Area (A^*/A_e) as Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
6	.000	.000	--	--	--
8	.006	.002	.001	.000	.000
10	.023	.011	.005	.002	.001
12	.050	.026	.015	.008	.005
14	.085	.047	.029	.018	.012
16	.125	.072	.046	.031	.021
18	.168	.099	.066	.046	.033
20	.214	.128	.087	.063	.046
30	.47	.30	.21	.16	.13
40	.75	.48	.35	.28	.22
50	1.04	.67	.50	.40	.33
60	1.33	.87	.65	.52	.43
80	1.92	1.26	.96	.78	.65
100	2.52	1.66	1.27	1.03	.87
120	3.12	2.07	1.58	1.29	1.09
140	3.73	2.47	1.90	1.55	1.31
160	4.33	2.87	2.21	1.81	1.54
180	4.93	3.28	2.53	2.07	1.76

Table C.6. Ratio of Cross-Sectional Area at Section '1' to Injection Tube Exit Area (A_1/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
6	.153	.027	--	--	--
8	.617	.335	.192	.100	.033
10	1.093	.652	.438	.303	.207
12	1.573	.973	.686	.508	.383
14	2.061	1.299	.940	.717	.562
16	2.552	1.628	1.190	.925	.740
18	3.035	1.951	1.446	1.136	.921
20	3.528	2.281	1.702	1.348	1.104
30	6.00	3.94	2.99	2.42	2.02
40	8.46	5.59	4.27	3.48	2.93
50	10.94	7.25	5.57	4.55	3.86
60	13.42	8.91	6.86	5.62	4.78
80	18.38	12.23	9.45	7.77	6.63
100	23.34	15.56	12.04	9.92	8.47
120	28.30	18.89	14.63	12.07	10.32
140	33.26	22.22	17.22	14.22	12.17
160	38.23	25.54	19.81	16.37	14.02
180	43.19	28.87	22.40	18.52	15.87

Table C.7. Ratio of Cross-Sectional Area at Section '2' to Injection Tube Exit Area (A_2/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
6	1.797	1.239	--	--	--
8	2.295	1.572	1.251	1.059	0.928
10	2.793	1.906	1.510	1.275	1.115
12	3.288	2.238	1.769	1.489	1.299
14	3.787	2.573	2.030	1.705	1.485
16	4.287	2.908	2.286	1.918	1.668
18	4.777	3.236	2.546	2.134	1.854
20	5.275	3.570	2.806	2.350	2.039
30	7.76	5.24	4.11	3.43	2.97
40	10.23	6.89	5.39	4.50	3.89
50	12.72	8.56	6.69	5.57	4.81
60	15.20	10.22	7.99	6.65	5.74
80	20.16	13.55	10.58	8.80	7.59
100	25.13	16.88	13.17	10.95	9.44
120	30.09	20.21	15.76	13.10	11.28
140	35.06	23.54	18.35	15.25	13.13
160	40.02	26.87	20.95	17.40	14.98
180	44.98	30.19	23.54	19.55	16.82

Table C.8. Ratio of Cross-Sectional Area at Section '4' to Injection Tube Exit Area (A_4/A_e) as a Function of the Primary and Secondary Air Nondimensional Mass Flow Parameters N_{g1} and N_{g2}

N_{g1}	N_{g2}				
	.2	.4	.6	.8	1.
6	6.813	4.701	--	--	--
8	8.797	6.031	4.800	4.068	3.573
10	10.777	7.359	5.834	4.926	4.310
12	12.756	8.685	6.866	5.783	5.047
14	14.733	10.011	7.899	6.639	5.783
16	16.709	11.336	8.930	7.495	6.520
18	18.685	12.661	9.962	8.351	7.256
20	20.66	13.99	10.99	9.21	7.99
30	30.53	20.61	16.15	13.48	11.67
40	40.41	27.22	21.30	17.76	15.35
50	50.28	33.84	26.46	22.04	19.02
60	60.15	40.46	31.61	26.31	22.70
80	79.89	53.69	41.91	34.86	30.06
100	99.62	66.93	52.22	43.41	37.41
120	119.36	80.16	62.53	51.96	44.76
140	139.10	93.40	72.83	60.51	52.12
160	158.84	106.63	83.14	69.06	59.47
180	178.58	119.87	93.44	77.61	66.82

Table C.9. Effect of Change of P_e on the Parameter P_{g1}/P_4 for $N_{g2}=1$ and $P_4=18$ bar

N_{g1}	P_e [bar] $\longrightarrow$	1	2	3
20		27.59	3.795	1.462
40		11.32	2.816	1.335
60		8.813	2.575	1.292
80		7.831	2.457	1.273
100		7.311	2.389	1.264

Table C.10. P_{g1}/P_4 as a Function of T_{0e}/T_{g1} for $N_{g2}=1$ and $T_{g1}=700^\circ\text{K}$

N_{g1}	T_{0e}/T_{g1}	
	1	.429
	($T_{0e}=700^\circ\text{K}$)	($T_{0e}=300^\circ\text{K}$)
20	27.59	14.95
40	11.32	8.870
60	8.813	7.569
80	7.831	7.012
100	7.311	6.703

APPENDIX D

DERIVATION OF THE APPROXIMATED STRAIGHT-LINE EQUATION
WHICH GIVES THE MAXIMUM VALUE OF THE RATIO OF
VESSEL INLET PRESSURE TO INJECTION PRESSURE

A simple expression for $[P_4/P_e]_{(\max)}$ as a linear function of N_{g1} will be derived. After replacing T_{01} by T_{g1} , eq. (4.77) can be rewritten as:

$$M_{2(\max)} = \left[\frac{\gamma_m R_m T_{02} (N_{g1} + N_{g2} + 1)^2}{\left[N_{g1} \sqrt{\frac{2 \gamma R T_{g1}}{(\gamma-1)}} + (1 + N_{g2}) \sqrt{\frac{\gamma_e R_e T_{0e}}{M_e^2 + \frac{(\gamma_e-1)}{2}}} \right]^2} - \frac{(\gamma_m-1)}{2} \right]^{-.5} \quad (D.1)$$

Expanding the polynomial and dividing numerator and denominator of the right-hand side of the equation by $(N_{g1})^2$:

$$M_{2(\max)} = \left\{ \gamma_m R_m T_{02} \left[1 + \frac{2 N_{g2}}{N_{g1}} + \frac{(N_{g2})^2}{(N_{g1})^2} + \frac{2}{N_{g1}} + \frac{2 N_{g2}}{(N_{g1})^2} + \frac{1}{(N_{g1})^2} \right] \right. \\ \left. \left[\frac{2 \gamma R T_{g1}}{(\gamma-1)} + \frac{2(N_{g2}+1)}{N_{g1}} \sqrt{\frac{2 \gamma R T_{g1} \gamma_e R_e T_{0e}}{(\gamma-1) \left[\frac{1}{M_e^2} + \frac{(\gamma_e-1)}{2} \right]}} \right. \right. \\ \left. \left. + \frac{(1+N_{g2})^2}{(N_{g1})^2} \left[\frac{2 \gamma_e R_e T_{0e}}{\frac{1}{M_e^2} + \frac{(\gamma_e-1)}{2}} \right] \right] - \frac{(\gamma_m-1)}{2} \right\}^{-.5} \quad (D.2)$$

When $N_{g1} \gg 1 N_{g2}$, $T_{02} \rightarrow T_{g1}$, $R_m \rightarrow R$, and $\gamma_m \rightarrow \gamma$. Neglecting terms varying with $1/(N_{g1})^2$:

$$M_{2(\max)} = \left[\frac{\gamma R T_{g1} \left(1 + \frac{2 N_{g2}}{N_{g1}} + \frac{2}{N_{g1}} \right)}{\left[\frac{2 \gamma R T_{g1}}{(\gamma-1)} + \frac{2(N_{g2}+1)}{N_{g1}} \sqrt{\frac{2 \gamma R T_{g1} \gamma_e R_e T_{0e}}{(\gamma-1) \left[\frac{1}{M_e^2} + \frac{(\gamma_e-1)}{2} \right]}} \right]^2} - \frac{(\gamma-1)}{2} \right]^{-.5} \quad (D.3)$$

This expression can be rewritten as

$$M_{2(\max)} = \left[\frac{N_{g1} + 2(N_{g2} + 1)}{\frac{2 N_{g1}}{(\gamma-1)} + 2(N_{g2}+1)} \sqrt{\frac{2 \gamma_e R_e T_{0e}}{\gamma R T_{g1} (\gamma-1) \left[\frac{1}{M_e^2} + \frac{(\gamma_e-1)}{2} \right]}} - \frac{(\gamma-1)}{2} \right]^{-.5} \quad (D.4)$$

or

$$(M_{2(\max)})^2 = \frac{\frac{2 N_{g1}}{(\gamma-1)} + 2(N_{g2}+1)}{2(N_{g2}+1) - (\gamma-1)(N_{g2}+1)} \sqrt{\frac{2 \gamma_e R_e T_{0e}}{\gamma R T_{g1} (\gamma-1) \left[\frac{1}{M_e^2} + \frac{(\gamma_e-1)}{2} \right]}} \quad (D.5)$$

Since $(M_{2(\max)})^2$ is a linear function of N_{g1} , eq. (D.5) can be expressed as:

$$(M_{2(\max)})^2 = C_1 N_{g1} + C_2 \quad (D.6)$$

Eq. (4.74) can be rewritten in terms of $M_{2(\max)}$ as:

$$\left(\frac{P_4}{P_e} \right)_{(\max)} = \left[\frac{\frac{(\gamma_m+1)(M_{2(\max)})^2}{2}}{1 + \frac{(\gamma_m-1)M_4^2}{2}} \right]^{\frac{\gamma_m}{(\gamma_m-1)}} \left[\frac{2 \gamma_m (M_{2(\max)})^2}{(\gamma_m+1)} - \frac{(\gamma_m-1)}{(\gamma_m+1)} \right]^{1/(1-\gamma_m)} \quad (D.7)$$

For $N_{g1} \gg 1 N_{g2}$ and for $M_4 \ll 1$

$$\left(\frac{P_4}{P_e} \right)_{(\max)} = \left[\frac{(\gamma+1)(M_{2(\max)})^2}{2} \right]^{\frac{\gamma}{(\gamma-1)}} \left[\frac{2 \gamma (M_{2(\max)})^2}{(\gamma+1)} - \frac{(\gamma-1)}{(\gamma+1)} \right]^{1/(1-\gamma)} \quad (D.8)$$

Rearranging,

$$\left(\frac{P_4}{P_e}\right)_{(\max)} = \left[\frac{\frac{(\gamma+1)(M_{2(\max)})^2}{2}}{\frac{2\gamma(M_{2(\max)})^2}{(\gamma+1)} - \frac{(\gamma-1)}{(\gamma+1)}} \right]^{\frac{\gamma}{(\gamma-1)}} \quad (D.9)$$

The assumption that $N_{g1} \gg 1$ N_{g2} implies that $(M_{2(\max)})^2 \gg 1$. For $(M_{2(\max)})^2 \gg 1$ the term $(\gamma-1)/(\gamma+1)$ may be neglected and eq. (D.9) may be written as:

$$\left(\frac{P_4}{P_e}\right)_{(\max)} = \left[\frac{\frac{(\gamma+1)(M_{2(\max)})^2}{2}}{\frac{2\gamma(M_{2(\max)})^2}{(\gamma+1)}} \right]^{\frac{\gamma}{(\gamma-1)}} \quad (D.10)$$

Rearranging,

$$\left(\frac{P_4}{P_e}\right)_{(\max)} = \left[\frac{\frac{(\gamma+1)}{2}}{(\gamma)[1/(\gamma-1)]} \right] (M_{2(\max)})^2 \quad (D.11)$$

After substituting $(M_{2(\max)})^2$ from eq. (D.6) the following straight-line equation is obtained:

$$\left(\frac{P_4}{P_e}\right)_{(\max)} = \left[\frac{\frac{(\gamma+1)}{2}}{(\gamma)[1/(\gamma-1)]} \right] (C_1 N_{g1} + C_2) \quad (D.12)$$

which holds in the limit for $N_{g1} \gg N_{g2} \approx 1$ and $M_4 \ll 1$.

APPENDIX E

COMPUTER PROGRAM USED FOR THE EXPERIMENTAL MODEL DESIGN


```

C          B1          AREA AT SECTION 1.
C          B2          "   "   "   2.
C          B3          "   "   "   3.
C
C      MACH NO.:
C          M3MAX        MAXIMUM MACH NUMBER AFTER NORMAL
C                        SHOCK FOR THE FORMATION OF A
C                        DISPERSE SHOCK
C      OTHER PARAMETERS:
C          Q            INJECTION TUBE WALL THICKNESS
C          WIDTH        NOZZLE WIDTH
C
C      ALL OTHER VARIABLES AS IN PROGRAM "GDI.FOR"
C
      REAL MS,M1,M2,M3,ME,M2MIN,M3MAX,L1,LE,M2A,M2B,NG1,NG2
      INTEGER PMODE,GRP,CSE
      COMMON DMT,DMG1,DMGE,G,R,GM,RM,GE,RE,M1,M2,ME,
$ A1,A2,AE,P1,P2,T01T1,T1,T01,T02T2,T2,T02,TE,GC
      PI=3.141592654
      READ (21,*) FLG1
      IF ((FLG1.EQ.1 ).OR.(FLG1.EQ.2 ).OR.(FLG1.EQ.3 )) GOTO 90
      WRITE(5,*)' CHECK FIRST LINE AT FILE FORM1.DAT'
      STOP
90      WRITE(5,*)' EXECUTING GDI2C.FOR, PROG. MODE:',FLG1
100     READ(21,*,END=500) PMODE
      IF (PMODE.NE.FLG1) GOTO 100
      IF (FLG1.EQ.1) GOTO 101
      IF (FLG1.EQ.2) GOTO 102
      IF (FLG1.EQ.3) GOTO 103
      STOP
101     READ(21,*)PMODE,G,R,DP,CCP,Q,WIDTH
      READ(21,*)PMODE
      IFILE=41
      QP=Q*1.E-3
      WIDTHP=WIDTH*1.E-3
      GOTO 109
102     READ(21,*) PMODE,G,R,DP,CCP,AEXTS,AEXT1,WIDTH
      READ(21,*)PMODE
      IFILE=42
      AEXTSP=AEXTS*1.E-6
      AEXT1P=AEXT1*1.E-6
      WIDTHP=WIDTH*1.E-3
      GOTO 109
103     READ(21,*) PMODE,G,R,DP,CCP,AEXTS,AEXT1,WIDTH
      READ(21,*)PMODE
      IFILE=43
      AEXTSP=AEXTS*1.E-6
      AEXT1P=AEXT1*1.E-6
      WIDTHP=WIDTH*1.E-3
109     IF (FLG1.EQ.1) GOTO 110

```

```

        IF (FLG1.EQ.2) GOTO 120
        IF (FLG1.EQ.3) GOTO 130
C   READ DATA IN.
110   READ(21,*,END=500) PMODE,GRP,CSE,DMP,NG1,NG2,
      $ TP,TG1,TG2,P1,P3,ME
      AE=' '
      A1=' '
      A2=' '
      AS=' '
      AEXTS=' '
      AEXT1=' '
C   THE FOLLOWING INSTRUCTION STOPS THE PROGRAM EXECUTION IF A ZERO (0)
C   IS ENCOUNTERED AT THE BEGINNING OF A LINE IN THE DATA FILE.
      IF(PMODE.NE.FLG1) GOTO 500
C   READ DATA OUT.
      WRITE(IFILE,590)PMODE,GRP,CSE,G,R,DP,CCP,Q,WIDTH
      WRITE(IFILE,610) DMP,NG1,NG2,TG1,TG2,TP,P1,P3,ME,AE,AS,A1,A2
C   CONVERT TO MKS
      P1=P1*1.E5
      P3=P3*1.E5
      DMP=DMP*1.E-3
      GOTO 155
120   READ(21,*,END=500) PMODE,GRP,CSE,DMP,NG1,NG2,
      $ TP,TG1,TG2,P1,P3,AE
      ME=' '
      A1=' '
      A2=' '
      AS=' '
C   THE FOLLOWING INSTRUCTION STOPS THE PROGRAM EXECUTION IF A ZERO (0)
C   IS ENCOUNTERED AT THE BEGINNING OF A LINE IN THE DATA FILE.
      IF(PMODE.NE.FLG1) GOTO 500
C   READ DATA OUT.
      WRITE(IFILE,595) PMODE,GRP,CSE,G,R,DP,CCP,
      $ AEXTS,AEXT1,WIDTH
      WRITE(IFILE,620) DMP,NG1,NG2,TG1,TG2,TP,P1,P3,ME,AE,AS,A1,A2
C   CONVERT TO MKS
      P1=P1*1.E5
      P3=P3*1.E5
      DMP=DMP*1.E-3
      AE=AE*1.E-6
      GOTO 155
130   READ(21,*,END=500) PMODE,GRP,CSE,NG1,NG2,
      $ TP,TG1,TG2,P1,P3,ME,AE
      DMP=' '
      A1=' '
      A2=' '
      AS=' '
C   THE FOLLOWING INSTRUCTION STOPS THE PROGRAM EXECUTION IF A ZERO (0)
C   IS ENCOUNTERED AT THE BEGINNING OF A LINE IN THE DATA FILE.
      IF(PMODE.NE.FLG1) GOTO 500
C   READ DATA OUT.

```

```

        WRITE(IFILE,595) PMODE,GRP,CSE,G,R,DP,CCP,
$ AEXTS,AEXT1,WIDTH
        WRITE(IFILE,630) DMP,NG1,NG2,TG1,TG2,TP,P1,P3,ME,AE,AS,A1,A2
C      CONVERT TO MKS
        P1=P1*1.E5
        P3=P3*1.E5
        AE=AE*1.E-6
C      I.  COMPUTE FLUID PROPERTIES.
155      RE= R*NG2/(NG2+1)
        GE=G*(NG2+(CCP))/(NG2+G*(CCP))
        CPECP=(NG2+(CCP))/(NG2+1)
C
        RER=RE/R
C
        RM=R*(NG1+NG2)/(NG1+NG2+1)
        GM=G*(NG1+NG2+(CCP))/(NG1+NG2+G*(CCP))
        CP2CP=(NG1+NG2+(CCP))/(NG1+NG2+1)
C
        RMR=RM/R
C
        WRITE(IFILE,655)PMODE,GRP,CSE
        WRITE(IFILE,660)GE,RER,CPECP,GM,RMR,CP2CP
C
C      II.  VERIFY IF THE FLOW IS POSSIBLE.
C      A.  COMPUTE THE MINIMUM MACH NO. WHICH ALLOWS THE FORMATION OF
C          A DISPERSE SHOCK.
        M2MIN=SQRT(G/GM/RMR)
C
C      B.  COMPUTE THE MAXIMUM POSSIBLE MACH NUMBER AFTER NORMAL SHOCK
C          WHICH ALLOWS THE FORMATION OF A DISPERSE SHOCK.
        M3MAX=((M2MIN**2+2./(GM-1.))/(2.*GM*M2MIN**2/(GM-1.)-1.))**.5
C
C      C.  COMPUTE THE MINIMUM PRESSURE RATIO WHICH ALLOWS THE FORMATION
C          OF A DISCONTINUOUS SHOCK.
        P3P2M=((GM+1.)/2.*M2MIN**2)/(1.+(GM-1.)/2.*M3MAX**2)**
$      (GM/(GM-1))
$      *(2.*GM*M2MIN**2/(GM+1.)-(GM-1.)/(GM+1.))**(1./(1.-GM))
C      COMPUTE ACTUAL PRESSURE RATIO
        P2=P1
        P3P2=P3/P2
        WRITE(IFILE,670)M2MIN,M3MAX,P3P2M,P3P2
C
C      COMPARE THE ACTUAL PRESSURE RATIO (P3P2) WITH THE MINIMUM
C      PRESSURE RATIO (P3P2M). IF (P3P2) IS GREATER THAN (P3P2M)
C      CONTINUE CALCULATIONS; OTHERWISE, WRITE A MESSAGE AND
C      START WITH A NEW CASE.
        IF(P3P2.LT.P3P2M) WRITE(IFILE,680)
C
C      III.  SOLVE THE SET OF EQUATIONS.
C*****

```

```

C
C CONDITIONS AT SECTION E
C
C*****
200    PE=P1
      P2=P1
C
      TOE=(CCP*TP+NG2*TG2)/(NG2+1)/CPECP
C
      IF(FLG1.NE.2 ) GOTO 210
      LE=(DMP*(1+NG2)/PE/AE)**2 * RE*TOE/GE
206    ME=SQRT((SQRT(1+2*(GE-1)*LE)-1)/(GE-1))
C
210    TOETE=1.+(GE-1.)/2.*ME**2
      TE=TOE/TOETE
      POEPE=TOETE**2*(GE/(GE-1.))
      POE=POEPE*PE
C
      IF(FLG1.EQ.1 ) AE=DMP*(1.+NG2)/PE/ME*SQRT(RE*TE/GE)
C
      IF(FLG1.EQ.3 ) DMP=PE*AE*ME/(NG2+1)*SQRT(GE/RE/TE)
C*****
C
C COMPUTE MASS FLOW RATES
C
C*****
      DMG1=DMP*NG1
      DMG2=DMP*NG2
C*****
C
C CONDITIONS AT SECTION 2
C
C*****
      T02=(TG1*NG1+CPECP*TOE*(NG2+1.))/(CP2CP*(NG1+NG2+1.))
      M2=((GM+1)/2/GM*P3/P2+(GM-1)/2/GM)**.5
      T02T2=1.+(GM-1.)/2.*M2**2
      T2=T02/T02T2
C
      A2=DMP*(NG1+NG2+1)/P2/M2*SQRT(RM*T2/GM)
      P02P2=T02T2**2*(GM/(GM-1.))
      P02=P02P2*P2
C
C*****
C
C CONDITIONS AT SECTION 3
C
C*****
      A3=A2
      T03=T02
C
      M3=((M2**2+2.)/(GM-1.))/(2.*GM*M2**2/(GM-1.))-1.))**.5

```

```

C
    T03T3=1.+(GM-1.)/2.*M3**2
    T3=T03/T03T3
C
    P3P2=(1+GM*M2**2)/(1+GM*M3**2)
    P3=P3P2*P2
    P03P3=T03T3** (GM/(GM-1.))
    P03=P03P3*P3
C*****
C
C    CONDITIONS AT SECTION 1
C
C*****
    T01=TG1
C
    PHI=(( (NG1+NG2+1)*M2*SQRT(GM*RM*T2)-(NG2+1)*ME*
$ SQRT(GE*RE*TE))/NG1)**2/G/R/T01
    M1=1./SQRT(1./PHI-(G-1.)/2.)
    T01T1=1.+(G-1)/2.*M1**2
    T1=T01/T01T1
C
    P01P1=T01T1** (G/(G-1.))
    P01=P01P1*P1
    PG1=P01
C
    A1=DMP*NG1/P1/M1*SQRT(R*T1/G)
C
C*****
C
C    CONDITIONS AT SECTION S
C
C*****
    T0S=TG1
    P0S=P01
    MS=1.
C
    T0STS=(G+1.)/2.
    TS=T0S/T0STS
C
    P0SPS=T0STS** (G/(G-1.))
    PS=P0S/P0SPS
C
    AS=DMP*NG1/PS*SQRT(R*TS/G)
C
C*****
C    AT THIS POINT THE SET OF EQUATIONS IS SOLVED.
C
C    ESTIMATE THE SOLDS VOLUME FRACTION FOR SECTIONS 'E' AND '4'
C    NOTE: THIS IS ONLY AN ESTIMATE SINCE THE ASSUMPTION
C           SVF=0 FOR THE DERIVATION OF EQUATIONS IMPLIES THAT
C           P,T,M, AND A ARE NOT EXACT EVEN FOR AN EXACT NON-NUMERICAL

```

```

C      SOLUTION. IN ADDITION THE EXPRESSION TO BE USED FOR SVF
C      IS ALSO AN APPROXIMATION.
      SVFE=PE/DP/R/TE/NG2
      SVF3=P3/DP/R/T3/(NG1+NG2)
C
C      COMPUTATION OF NOZZLE VERTICAL DIMENSION
      IF (FLG1.NE.1) GOTO 493
      IF(Q.NE.0) GOTO 492
491    BS=' '
      B1=' '
      B2=' '
      B3=' '
      GOTO 495
492    DEXTS=SQRT(4*AE/PI)+2*QP
      AEXTSP=PI*DEXTS**2/4
      AEXT1P=AEXTSP
493    IF ((AEXTSP.EQ.0).OR.(AEXT1P.EQ.0).OR.(WIDTHP.EQ.0)) GOTO 491
      BS=(AS+AEXTSP)/WIDTHP
      B1=(A1+AEXT1P)/WIDTHP
      B2=A2/WIDTHP
      B3=B2
C      CONVERT TO OUTPUT UNITS
C      [M] TO [MM2]
      BS=BS*1.E3
      B1=B1*1.E3
      B2=B2*1.E3
      B3=B3*1.E3
C      [KG/S] TO [G/S]
495    DMP=DMP*1.E3
      DMG1=DMG1*1.E3
      DMG2=DMG2*1.E3
C      [M2] TO [MM2]
      AS=AS*1.E6
      A1=A1*1.E6
      A2=A2*1.E6
      A3=A3*1.E6
      AE=AE*1.E6
C      [PA] TO [BAR]
      PS=PS*1.E-5
      P1=P1*1.E-5
      P2=P2*1.E-5
      P3=P3*1.E-5
      PE=PE*1.E-5
      PG1=PG1*1.E-5
C
      POS=POS*1.E-5
      P01=P01*1.E-5
      P02=P02*1.E-5
      P03=P03*1.E-5
      POE=POE*1.E-5
C

```

```

C   ADDITIONAL COMPUTATIONS
C
      ASAE=AS/AE
      A1AE=A1/AE
      A2AE=A2/AE
      A3AE=A3/AE
      AEAE=AE/AE
C
C   PRESSURE RATIOS
      PSPG1=PS/PG1
      P1PG1=P1/PG1
      P2PG1=P2/PG1
      P3PG1=P3/PG1
      PEPG1=PE/PG1
      PG1PG1=1.
      POSPG1=POS/PG1
      P01PG1=P01/PG1
      P02PG1=P02/PG1
      P03PG1=P03/PG1
      POEPG1=POE/PG1
C   TEMPERATURE RATIOS
      TSTG1=TS/TG1
      T1TG1=T1/TG1
      T2TG1=T2/TG1
      T3TG1=T3/TG1
      TETG1=TE/TG1
      TG1TG1=1.
      TOSTG1=TOS/TG1
      T01TG1=T01/TG1
      T02TG1=T02/TG1
      T03TG1=T03/TG1
      TOETG1=TOE/TG1
C
C
      WRITE(IFILE,690)
      WRITE(IFILE,700)AS,A1,A2,A3,AE,ASAE,A1AE,A2AE,A3AE,AEAE
      IF ((BS.EQ.' ').OR.(B1.EQ.' ').OR.(B2.EQ.' ')) GOTO 497
      WRITE(IFILE,710)BS,B1,B2,B3
      GOTO 498
497  WRITE(IFILE,715)BS,B1,B2,B3
498  WRITE(IFILE,720)MS,M1,M2,M3,ME
      WRITE(IFILE,730)PG1,PS,P1,P2,P3,PE,
$ PG1PG1,PSPG1,P1PG1,P2PG1,P3PG1,PEPG1,
$ PG1,POS,P01,P02,P03,POE,
$ PG1PG1,POSPG1,P01PG1,P02PG1,P03PG1,POEPG1
      WRITE(IFILE,740)TG1,TS,T1,T2,T3,TE,
$ TG1TG1,TSTG1,T1TG1,T2TG1,T3TG1,TETG1,
$ TG1,TOS,T01,T02,T03,TOE,
$ TG1TG1,TOSTG1,T01TG1,T02TG1,T03TG1,TOETG1
C   WRITE(IFILE,750)AE,ME,POE,PE,TOE,TE
C

```

```

        WRITE(IFILE,760)DMG1,DMG2,DMP
        WRITE(IFILE,790)SVFE,SVF3
        GOTO 109
500      IF (IFILE.EQ.0) WRITE(IFILE,770)
        WRITE(5,780) IFILE
        STOP
590      FORMAT('1',///T5,'PROG. MODE:',I2,5X,'GROUP:',I2,5X,'CASE:',I2
$//T12,'-LOAD DATA-',//T12,'FLOW PROPERTIES'
$ /T12,'G=',F10.4
$ /T12,'R=',F10.4,' N-M/KG-K'
$ /T11,'DP=',F10.4,' KG/M3'
$ /T9,'C/CP=',F10.4
$ //T10,'INJECTION TUBE THICKNESS: ',F9.2,' MM'
$ //T10,'NOZZLE WIDTH: ',F9.2,' MM')
595      FORMAT('1',///T5,'PROG. MODE:',I2,5X,'GROUP:',I2,5X,'CASE:',I2
$//T12,'-LOAD DATA-',//T12,'FLOW PROPERTIES'
$ /T12,'G=',F10.4
$ /T12,'R=',F10.4,' N-M/KG-K'
$ /T11,'DP=',F10.4,' KG/M3'
$ /T9,'C/CP=',F10.4
$ //T5,'      INJECTION TUBE DIMENSIONS:'
$/T5,' EXTERNAL CROSS SECTIONAL AREA AT SECTION S: ',
$ 'AEXTS= ',F8.3,' SQ.MM'
$/T5,' EXTERNAL CROSS SECTIONAL AREA AT SECTION 1: ',
$ 'AEXT1= ',F8.3,' SQ.MM'
$ //T10,'NOZZLE WIDTH: ',F9.2,' MM')
605      FORMAT(A1)
610      FORMAT(/
$ /T10,'DMP=',F10.3,' KG/S'
$ /T10,'NG1=',F10.3
$ /T10,'NG2=',F10.3
$ /
$ /T10,'TG1=',F10.2,' K'
$ /T10,'TG2=',F10.2,' K'
$ /T10,' TP=',F10.2,' K'
$ /
$ /T11,'P1=',F10.3,' BAR'
$ /T11,'P3=',F10.3,' BAR'
$ /
$ /T11,'ME=',F10.5
$ /
$ /T13,'AE=',A3
$ /T13,'AS=',A3
$ /T13,'A1=',A3
$ /T13,'A2=',A3
$ )
620      FORMAT(/
$ /T10,'DMP=',F10.3,' KG/S'
$ /T10,'NG1=',F10.3
$ /T10,'NG2=',F10.3
$ /

```

```

$ /T10,'TG1=',F10.2,' K'
$ /T10,'TG2=',F10.2,' K'
$ /T10,' TP=',F10.2,' K'
$ /
$ /T11,'P1=',F10.3,' BAR'
$ /T11,'P3=',F10.3,' BAR'
$ /
$ /T13,'ME=',A3
$ /
$ /T13,'AE=',F8.5,' SQ.IN'
$ /T13,'AS=',A3
$ /T13,'A1=',A3
$ /T13,'A2=',A3
$ )
630   FORMAT(/
$ /T10,'DMP=',A3
$ /T10,'NG1=',F10.3
$ /T10,'NG2=',F10.3
$ /
$ /T10,'TG1=',F10.2,' K'
$ /T10,'TG2=',F10.2,' K'
$ /T10,' TP=',F10.2,' K'
$ /
$ /T11,'P1=',F10.3,' BAR'
$ /T11,'P3=',F10.3,' BAR'
$ /
$ /T11,'ME=',F10.4,
$ /
$ /T11,'AE=',F8.5,' MM2'
$ /T11,'AS=',A3
$ /T11,'A1=',A3
$ /T11,'A2=',A3
$ )
655   FORMAT('1'////T5,'PROG. MODE:',I2,5X,'GROUP:',I2,5X,'CASE:',I2
$ //T12,'-RESULTS-')
660   FORMAT(T10,'FLUID PROPERTIES'/T10,'GE=',F8.5,T25,'RE/R=',
$ F8.5,T43,'CPE/CP=',F8.5/T10,'GM=',F8.5,T25,'RM/R=',
$ F8.5,T43,'CP2/CP=',F8.5)
670   FORMAT(/T5,'M2MIN=',F8.5/T5,'M3MAX=',F8.5/
$ T5,'(P3/P2)MIN=',F8.4/T10,'P3/P2=',F8.4)
680   FORMAT(T5,'THIS FLOW IS NOT POSSIBLE. SHOCK WAVE WILL NOT',
$ /T5,'FORM SINCE (P3/P2) IS LESS THAN (P3/P2)MIN .'
$ /T5,'(P3/P2)MIN IS THE MINIMUM PRESSURE REQUIRED FOR'
$ /T5,'FORMATION OF A DISPERSE SHOCK.')
690   FORMAT(/T7,'SECTION:',4X,'STAGNATION',6X,'S',9X,'1',9X
$ , '2',9X,'3',9X,'E'
$ /T21,'CHAMBER',3X,'(THROAT)')
700   FORMAT(T7,'A [MM]',T29,5(1X,F9.5)
$ //T7,'A/AE',T29,5F10.5/)
710   FORMAT(T7,'B [MM]',T29,4(1X,F9.2)/)
715   FORMAT(T7,'B [MM]',T29,4(1X,A9)/)

```

```

720     FORMAT(T7,'MACH NO.',T29,5(2X,F8.5))
730     FORMAT(/T7,'P [BAR]',T19,6(1X,F9.3)
$ //T7,'P/PG1',T19,6(X,F9.5)
$ ///T7,'PO [BAR]',T19,6(X,F9.3)
$ //T7,'PO/PG1',T19,6(X,F9.5))
740     FORMAT(/T7,'T [K]',T19,6(1X,F9.2)
$ //T7,'T/TG1',T19,6(X,F9.5)
$ ///T7,'TO [K]',T19,6(X,F9.2)
$ //T7,'TO/TG1',T19,6(X,F9.5))
750     FORMAT(/T20,'INJECTION TUBE'/T15,'AE=',F8.5,' MM2',
$ T15,'ME=',F9.5//T15,'POE=',F8.2,4X,'PE=',F8.3,' BAR'//
$ T15,'TOE=',F8.2,' K',4X,'TE=',F8.2,' K')
760     FORMAT(/T12,'MASS FLOW RATE OF PRIMARY AIR =',F10.2,' G/S'
$ /T10,'MASS FLOW RATE OF SECONDARY AIR =',F10.2,' G/S'
$ /T20,'SOLIDS MASS FLOW RATE =',F10.2,' G/S')
770     FORMAT(/' NO DATA WAS READ. NO CALCULATIONS WERE MADE.'
$ / ' CHECK FORM1.DAT.')
780     FORMAT(/' RESULTS ARE IN FILE FOR',I2,'.DAT')
790     FORMAT(/T11,'SOLIDS VOLUME FRACTION',
$/T11,'SVFE=',E10.2/T11,'SVF4=',E10.2)
      END

```

APPENDIX F

TEST FACILITY

The test facility has been previously developed by Dr. R. J. Krane and M. Sumner as a project for a senior thesis. It is located at room 204 Dougherty Hall, University of Tennessee at Knoxville. A schematic view of the test facility is shown in Figure F.1. It consists of a system shutoff valve, two quick action valves, two pressure regulators, two rotameter flowmeters, a low pressure-differential feeding system, a stagnation chamber, a test section, a baghouse filter, and an exhaust fan. The low-pressure-differential feeding system consists of a solids hopper a mixing tank, and a magnetic vibratory solids feeder which pours the solids into the injection tube. The air compressors and the oil scrubbers and air driers are part of a major compressed air supply system.

This test facility, however, was not in proper order for running experimental tests and it was not completely instrumented. Some modifications were required before the test facility was ready to function properly. The work done in the laboratory can be summarized in the following list:

1. replacement of the two rotameters;
2. design and replacement of the vibratory feeder through;
3. replacement of funnel inside the mixing tank;
4. design of solids stirring system inside solids hopper;
5. replacement of rigid pipes by flexible hoses at the exit of rotameters;
6. installation of pressure and temperature ports at stagnation chamber, mixing tank, and exit sections of the two rotameters;
7. design of injection tube orientation and positioning system;

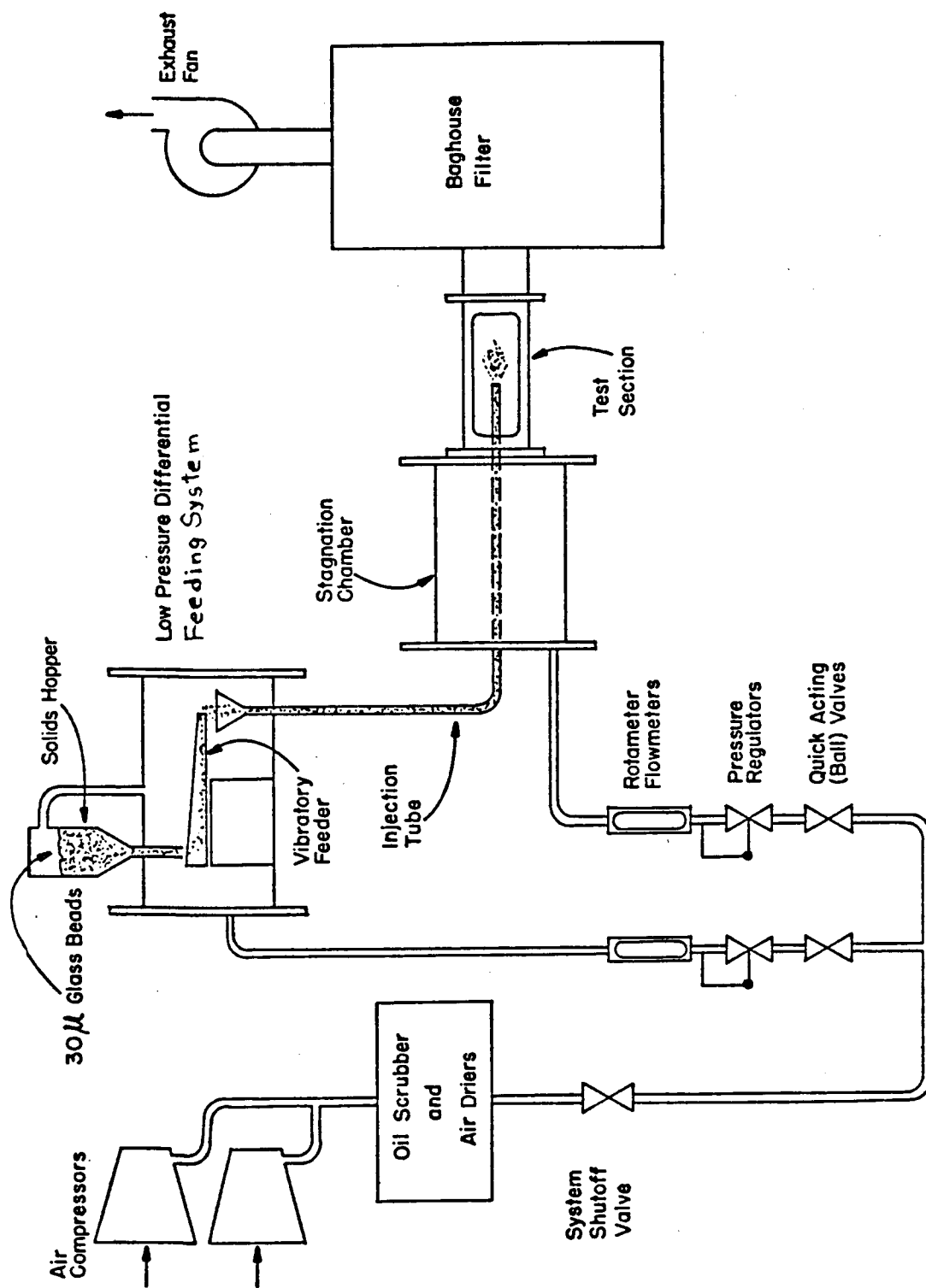


Figure F.1. Schematic View of the Gas-Dynamic Injector Test Facility

8. installation of pressure ports at injection tube (inside stagnation chamber);
9. improvization of a method that avoids leakage through nozzle assembly;
10. replacement of nozzle assembly windows;
11. adaptation of the "scanivalve" for pressure measurement at 26 ports;
12. design and installation of leak-proof thermocouple connections;
13. installation of an electronic switch for the magnetic vibratory feeder;
14. design of a computer program in BASIC language to be used by a Hewlett-Packard computer that works in conjunction of a data acquisition and control unit allowing the automatic reading of pressure and temperatures during a test.

Figure F.2 is an isometric view of the test facility showing all major components except the System Shutoff Valve and the Exhaust Fan.

Instrumentation and Special Devices

Rotameter Flowmeters

Primary air rotameter.

Brand: Fischer and Porter

Serial: X61-4037/1

Air Equivalent: 174 SCFM

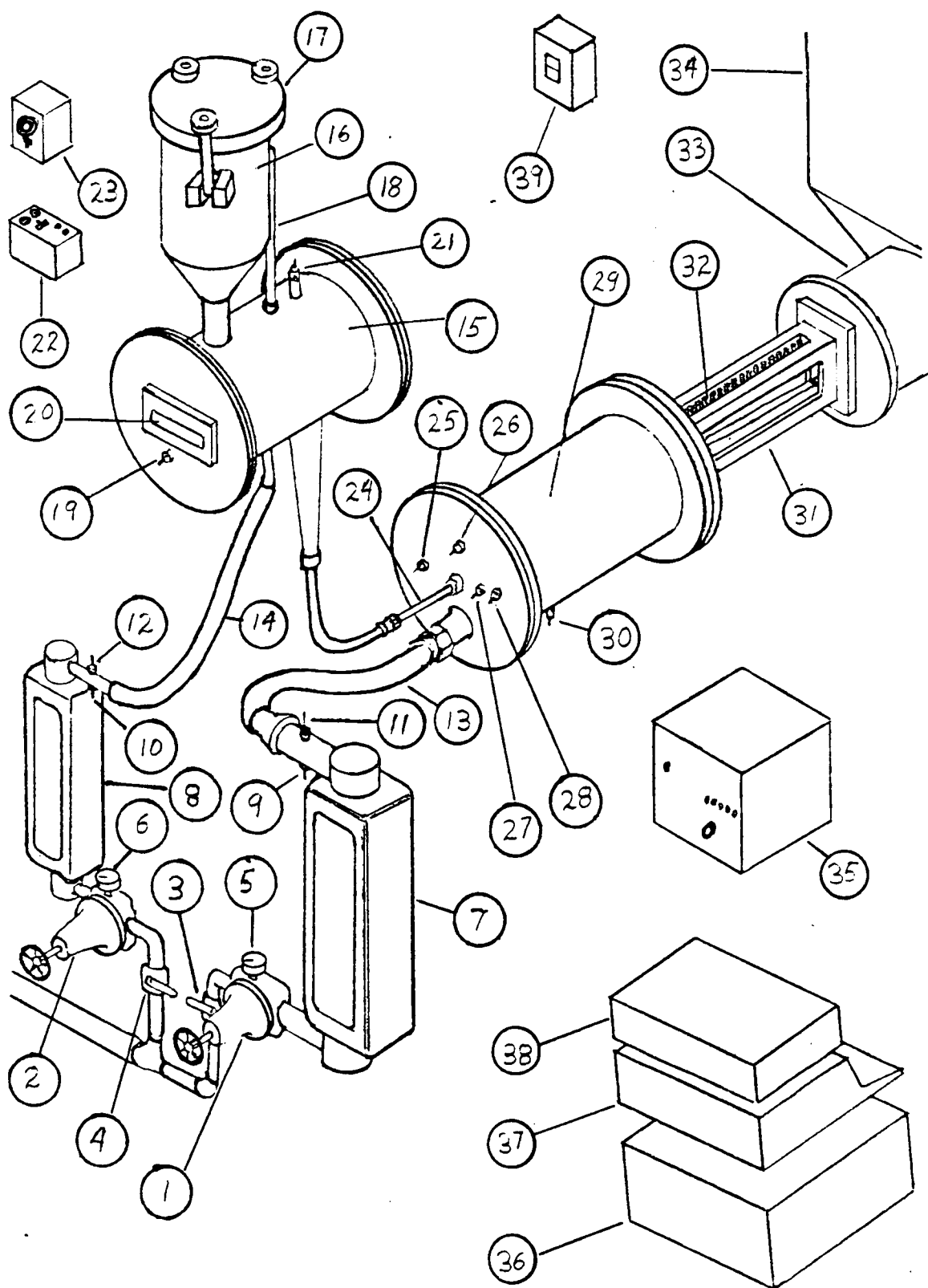


Figure F.2. The Test Facility

1. Primary Gas Pressure Regulator
2. Secondary Gas Pressure Regulator
3. Primary Gas Quick Action Valve (Ball Valve)
4. Secondary Gas Quick Action Valve (Ball Valve)
5. Primary Gas Manometer (160 psig max.)
6. Secondary Gas Manometer (160 psig max.)
7. Primary Gas Rotameter
8. Secondary Gas Rotameter
9. Pressure station
10. Pressure station
11. Temperature station
12. Temperature station
13. Primary Air Interconnecting Hose
14. Secondary Air Interconnecting Hose
15. Mixing Tank
16. Solids Hopper (Bin)
17. Cover
18. Breathing Duct
19. Pressure Station
20. Window
21. Pressure Relief Valve (60 psig)
22. Electronic Switch
23. Magnetic Feeder Controller Box
24. Injection Tube
25. Temperature station
26. Pressure Station
27. Pressure Station
28. Pressure Station
29. Stagnation Chamber
30. Pressure Relief Valve (60 psig)
31. Nozzle Block Assembly
32. Pressure Stations
33. Interconnecting Duct
34. Baghouse Filter
35. Scanivalve
36. Data Aquisition/Control Unit HP 3497A (DA/C Unit)
37. Computer HP 9826
38. Printer HP 2671G
39. Exhaust Fan Main Switch

Figure F.2. (Continued)

Secondary air rotameter.

Brand: Fischer and Porter

Serial: X4-4023/1

Air Equivalent: 4.6 SCFM

Scanivalve. The scanivalve (Figure F.3) is a pressure transducer attached to a valve that connects to 48 pressure ports (one at a time) distributed in a circumference. The valve rotates by the action of a solenoid activated by an electronic signal from the "timer output" of the DA/C unit (blue wire). The scanivalve has two output signals: one is the pressure signal as a function of the voltage and the other is the indicator for home position (port 48). An output of approximately 5 Volts from the red and black wires indicates that port 48 is on position. This signal goes into channel 41 of the DA/C unit. The pressure transducer sends .8 mV/psi or 11.6 mV/bar through the yellow and green wires. They are connected to channel 42 of the DA/C unit. The scanivalve scans ports at a rate of about 7 ports per second (maximum). In the front pannel there is a button that triggers the solenoid manually and there are five leds which indicate the scanivalve port position in a binary code.

Thermocouples. Type T: Copper vs. Copper-Nickel (copper-constantan). There are four of them connected to channels 46, 47, 48, and 49. An additional thermocouple connected to channel 45 gives the reference temperature of 0°C. It is exposed to a water-ice bath.

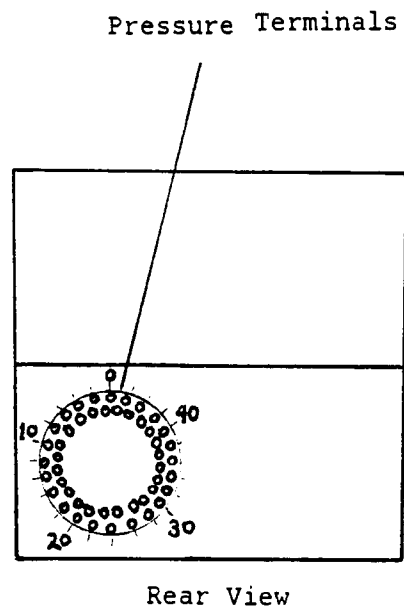
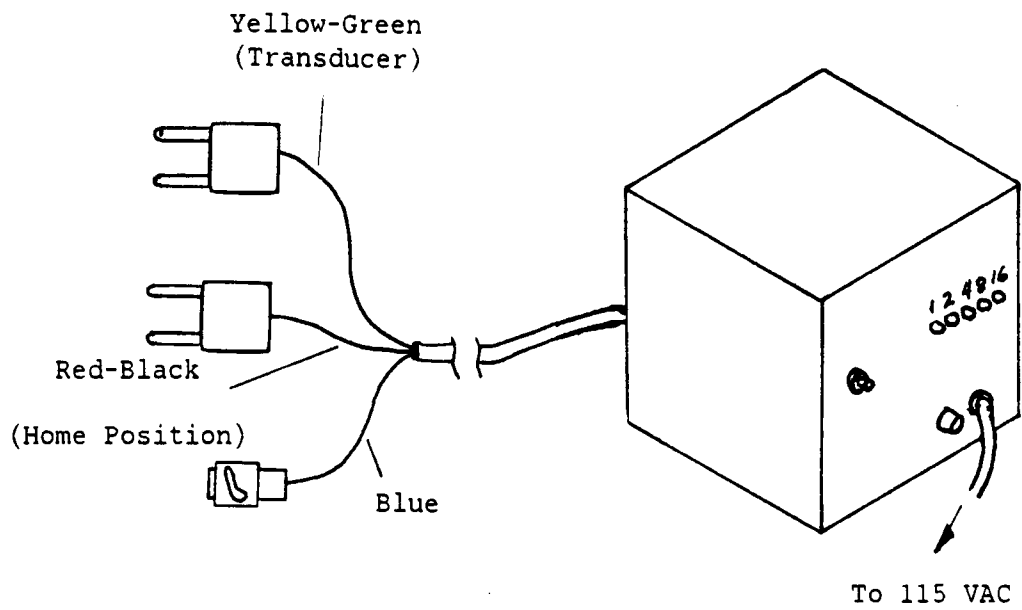


Figure F.3. Scanivalve

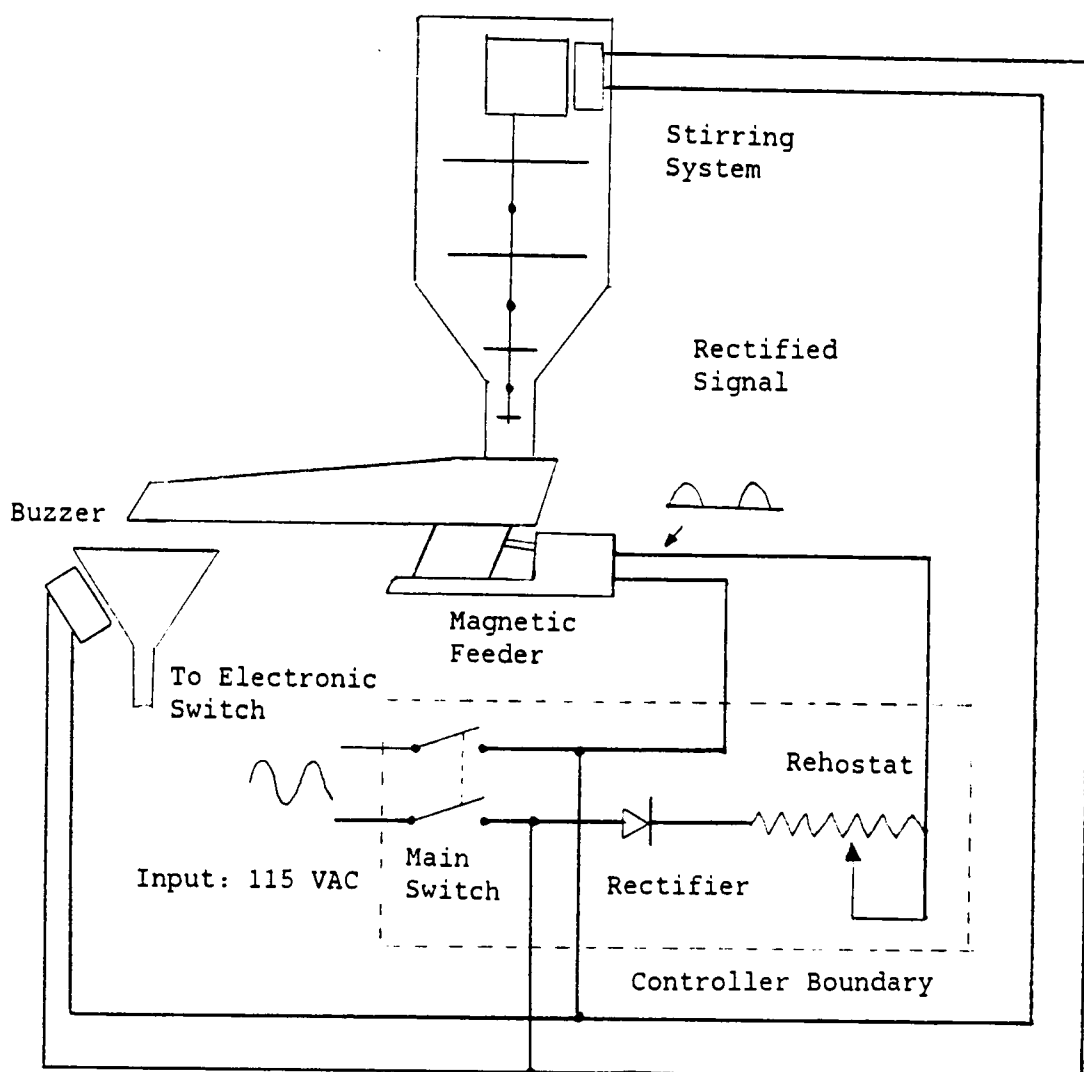
Magnetic Feeder Controller. The magnetic feeder controller (Figure F.4) is a rehostat that controls the amplitude of vibration of the magnetic feeder. It has a rectifier that sends half of the 115 VAC electricity to the magnetic vibratory feeder. The magnetic feeder control is located on one side of the mixing tank and has one outlet plug that connects to a 115 VAC. This plug is connected to an electronic switch operated by the DA/C unit.

Electronic Switch. The electronic switch sends an output of 115 VAC with an input voltage from 3 to 5 VDC. This switch turns the magnetic feeder on and off eliminating voltage peaks otherwise transmitted to the power line if a mechanical switch were used. Using conventional switches, these voltage peaks are transmitted via the power line to the scanivalve triggering the solenoid and shifting the scanner position when it is not desired. The electronic switch receives the input signal from the DA/C unit which, in turn, is controlled by a command in the main computer program.

Data Acquisition/Control Unit HP 3497A. This is the interface between the pressure and temperature transducers and the computer HP 9826. The connections at the rear panel are shown schematically in Figure F.5.

Terminal Connections.

The pressure port numbers and the temperature channels are shown schematically in Figure F.6.



Controller: FMC Model FC-TO
 115 VAC, 60 Hz,
 .35 A

Figure F.4. Magnetic Feeder Controller and Internal Circuit

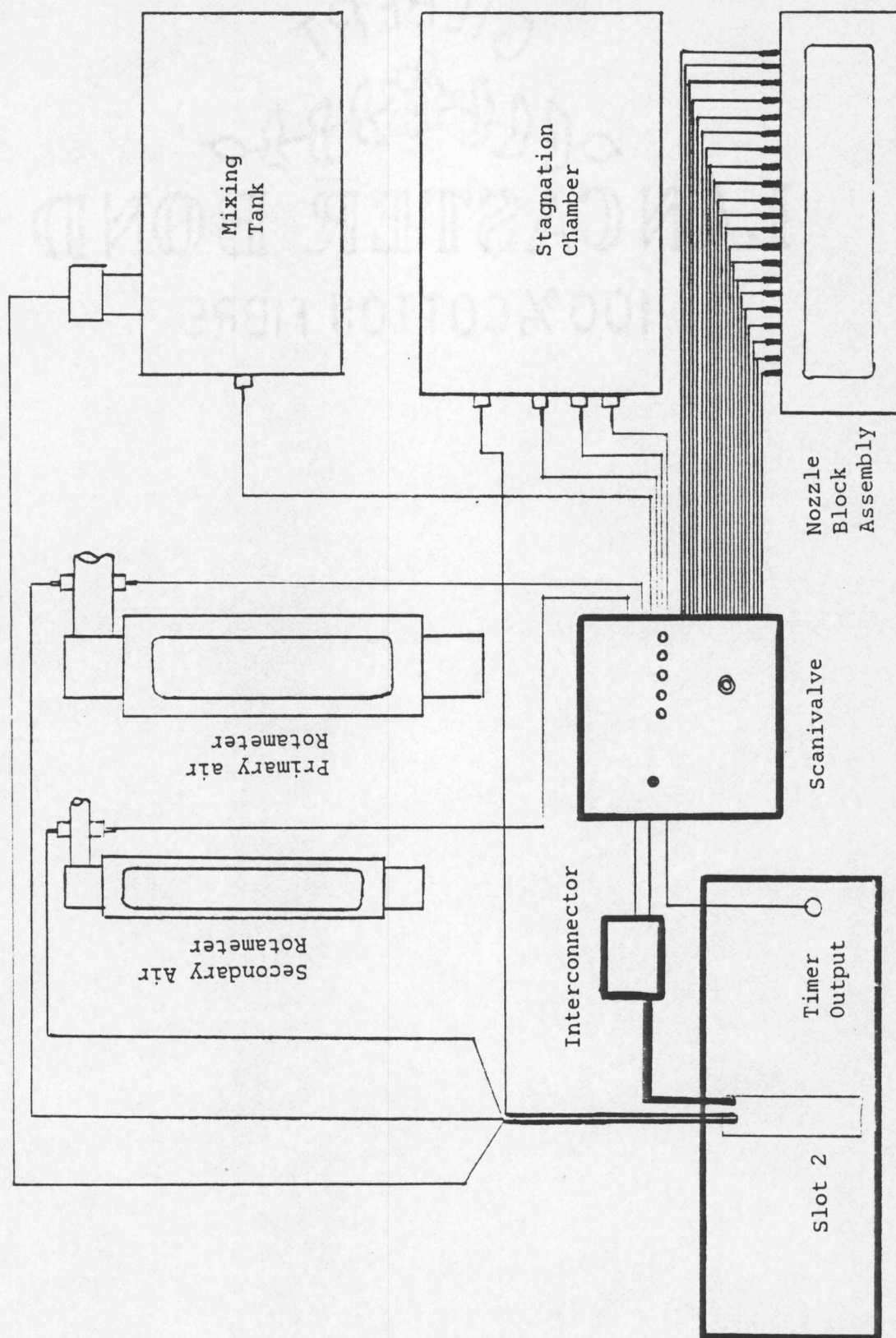


Figure F.5. Diagram of Pressure Lines and Thermocouple Connections

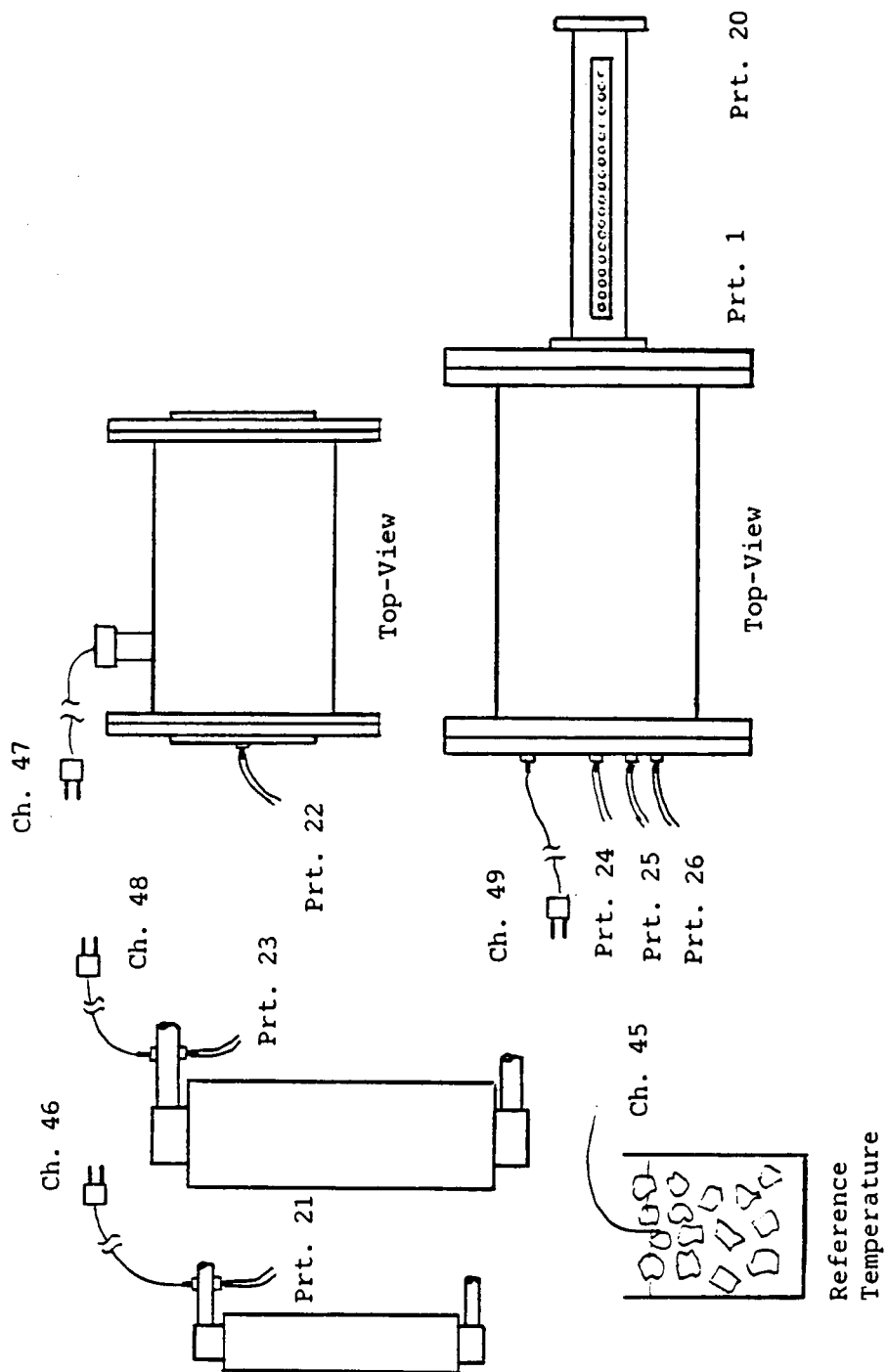


Figure F.6. Pressure Ports and Temperature Channels

Pressure ports:

Port No.	
0	Reference Error Pressure
1	Nozzle Block
2	.
3	.
4	.
5	.
6	.
7	.
8	.
9	.
10	.
11	.
12	.
13	.
14	.
15	.
16	.
18	.
19	.
20	.
21	Secondary Air Rotameter (Exit Section)
22	Mixing Tank
23	Primary Air Rotameter (Exit Section)
24	Stagnation Chamber
25	Injection Tube (Upstream)
26	Injection Tube (Downstream)

Temperature channels:

Channel No.	
45	Ice Reference Point
46	Secondary Air Rotameter Exit
47	Mixing Tank
48	Primary Air Rotameter Exit
49	Stagnation Chamber

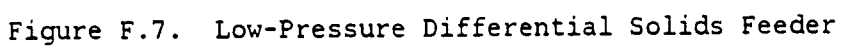
Figure F.6. (Continued)

Modification of Low-Pressure Feeding System

Figure F.7 shows the low-pressure feeding system. The vibratory feeder trough was redesigned in order to have a smooth and constant flow of solids with good repeatability and quick response to the controller setting. The new trough was built lighter with plexiglas. An upper wall and a mesh were added as key features. The metering mesh located at the exit breaks down big agglomerates and offers a restriction to the flow so that the solids always fill the entire passage. Thus, a constant mass of solids is present which provides better control. In the previous trough which had a free solids surface, any disturbance in the flow occurring inside the hopper have the effect of producing waves in the free solids surface. This results in inertia changes and irregularities in the flow discharge. A flexible junction between the hopper discharge section and the trough prevents damping of trough vibration and at the same time prevents solids leakage.

A stirring system located inside the solids hopper was designed to prevent solids clogging at the hopper discharge and solids compactation so that a constant flow with a uniform velocity profile are developed in the hopper.

The funnel at the discharge of the trough was replaced with a lighter and smaller funnel with a buzzer attached to it. The vibrations from the buzzer prevent solids to adhere and deposit at the walls. The funnel rests on a rubber ring at the top of a cylindrical support with holes allowing the air to enter.



- 1 Buzzer
- 2 Funnel
- 3 Funnel Stand
- 4 Vents
- 5 Rubber
- 6 Mesh
- 7 Trough
- 8 Upper Wall
- 9 Solids Passage
- 10 Trough Inlet Adaptor
- 11 Rubber Junction
- 12 Adaptor
- 13 Pin
- 14 Shaft Supporter
- 15 Shaft
- 16 Rods
- 17 Mesh
- 18 Shaft Junction
- 19 Electric Motor (Speed: 6 RPM, Torque: 30 oz.-in.)
- 20 Wall
- 21 Screens

Figure F.7. (Continued)

Air flow deflectors and screens were placed in the air inlet region. This was done to prevent the solids falling into the funnel from being blown out because of turbulence in the air.

Test Procedure

1. Shut off all valves.
2. Set pressure regulators to zero pressure (turn handle counter-clockwise all the way back).
3. Open system main valve (shutoff ball valve).
4. Turn on exhaust fan.
5. Open ball valves for primary and secondary air.
6. Set desired flow of primary air by rotating pressure regulator handle clockwise.
7. Set desired flow of secondary air by rotating pressure regulator handle clockwise.
8. Turn on magnetic feeder.
9. Take measurements.
10. Turn off magnetic feeder.
11. Set pressure regulators of secondary air to zero pressure (turn handle counter-clockwise all the way back).
12. Set pressure regulators of primary air to zero pressure (turn handle counter-clockwise all the way back).
13. Close ball valves for primary and secondary air.
14. Turn off exhaust fan.
15. Close system main valve (shutoff ball valve).

APPENDIX G

COMPUTER PROGRAM LISTINGS FOR
EXPERIMENTAL DATA AQUISITION

```

1  !PROGRAM: GDIEXP (GAS-DYNAMIC INJECTOR
2  !      EXPERIENCE)
3  !CREATED: OCTOBER 25,1984
4  !
5  !
6  ! THIS PROGRAM IS DESIGNED TO COLLECT
7  ! DATA FROM PRESSURE AND TEMPERATURE
8  ! TRANSDUCERS WHEN RUNNING A TEST IN THE
9  ! GAS-DYNAMIC INJECTOR.
10 ! THE RESULTS ARE PRINTED AND A PLOT OF PRESSURE
11 ! DISTRIBUTION IS CREATED. WHEN GIVING ROTAMETER
12 ! READINGS, THE PROGRAM COMPUTES THE MASS
13 ! FLOW RATE OF THE FLOWING GAS.
14 ! THE FOLLOWING DATA FILES HAVE TO BE
15 ! CREATED BEFORE RUNNING GDIEXP:
16 ! FILE          F.TYPE   REC/FILE  BYTE/REC
17 ! "GDIgDAT"      BDAT      1         15400
18 ! "VTconv"       BDAT      1         9320
19 ! PROGRAM VTC HAS TO BE RUN ONLY ONCE
20 ! BEFORE RUNNING GDIEXP FOR THE FIRST TIME.
21 ! UPDATED: MAR.,12,1985
22 !+++++
23 ALPHA OFF
24 GRAPHICS OFF
25 GINIT
26 WINDOW -30,210,-10,150
27 DEG
28 PRINTER IS 1
29 PRINT CHR$(12)      ! CLEAR SCREEN
30 PRINT "      EXECUTING GDI..."
31 PRINT
32 ALPHA ON
33 !+++++
34 CLEAR 709
35 OPTION BASE 1
36 INTEGER Flag,Flag1,Flag2,Flag3,Flag4,Flag5,Flag6,Flag7,
37 Cflag,Iflag
38 INTEGER Q,Ic,I,J,K,Ilimit
39 INTEGER Plotj(1:7500),Allplot(1:7500)
40 ! GENERAL CASE: j
41 COM /B10/ REAL Qig1,Qig2
42 COM /B11/ REAL Dit(1:3),Width
43 COM /B12/ REAL H(1:20)
44 COM /B13/ REAL Xexit
45 COM /B14/ REAL P(1:48),Pr(1:48)
46 COM /B15/ REAL Dmg1,Dmg2,Dmp
47 COM /B16/ REAL Temp(45:49)
48 COM /B18/ Month$(10),Day,Year$(5)
49 COM /B19/ Hour,Min,Sec,D$(2)
50 COM /B20/ REAL Patm1,Patm2,Patm3
51 COM /B21/ INTEGER Graph(1:7500)
52 COM /B22/ INTEGER Qmax

```

```

56 COM /B23/ REAL Time
57 COM /B24/ REAL Tapsep
58 COM /B25/ REAL Pr2(25:26)
59 !
60 REAL Kpt1,Kpt2
62 REAL Vp(0:47,0:11),Vt(45:49,0:11),Vavg(45:49),Vref(45:49),
Qa(1:50)
63 !
64 !
72 COM /Vt/ INTEGER Tmin,Tmax,REAL Vtable(-273:890)
73 ! CONSTANTS
74 Tapsep=19.05 ! [mm]SEPARATION BETWEEN TAPS
75 Gc=32.174 ! [(Lb-Ft/Sec.Sq)/Lbf] OR [Ft/Sec.Sq]
76 R=53.34 ! [Ft-Lbf/Lb-R]IDEAL GAS AIR CONSTANT
77 G=1.4 ! SP. HEAT RATIO
78 Kpt1=.00075 ! V/psi PRESSURE TRANSDUCER
79 Kpt2=.010885 ! V/bar
81 ! DATA AQUISITION PARAMETERS
82 Y1=.01 !sec/PORT
83 N1=1 !SAMPLE/PORT
84 S1=.01 !sec/SAMPLE
85 N2=1 !SAMPLE/CHANNEL
86 S2=.01 !sec/SAMPLE
87 !
88 ! DESCRIPTION OF ARRAYS USED
89 ! Dit INJECTION TUBE DIAMETER
90 ! (1) AT THE THROAT
91 ! (2) EXTERIOR AT I.T.E.P.
92 ! (3) INTERIOR AT I.T.E.P.
93 !
98 ! Graph GRAPHICS ARRAY(CLEAR PLOTS)
99 ! Allplots ARRAY CONTAINING ALL PLOTS
100 ! Plotj A PARTICULAR PLOT
101 !+++++
102 Flag=0 ! CONTROL PARAMETERS
103 Flag1=0
104 Flag2=0 ! PRESSURE DIAGRAM RESET
105 Flag3=0 ! SCANIVALVE RESET
106 Flag4=1 ! PRINT RESULTS (DEFAULT)
107 Flag5=0 ! LOAD GRAPHICS FROM Graph
108 Flag7=0 ! LOAD GDATA FORM GDIGCLRPLT
109 !
110 !
111 Testi=1
112 !
113 !-----
114 ! LOADING NOZZLE/INJECTION TUBE/PRESSURE
115 ! DIAGRAM, AND NOZZLE DIMENSIONS.
116 !
117 PRINT " IF 'GDIGDAT' CONTAINS DATA PREVIOUSLY STORED"
118 PRINT " PRESS <CONTINUE>"

```

```

119 PRINT
120 PRINT " OTHERWISE ENTER <1>"
121 Flag7=0
122 INPUT Flag7
123 IF Flag7=0 THEN
124     CALL Datagraph(0) ! LOAD GRAPHIC
125 ELSE
126     ! SET DEFAULT PARAMETERS
127     Flag5=1
128     READ Dit(*)
129     READ Width
130     FOR I=1 TO 20
131         H(I)=0.
132     NEXT I
133     READ H(1),H(5),H(15),H(20)
134     READ Xexit
135     DATA 4.24,3.86,3.53          ![mm] Dit
136     DATA 7.9375 ![mm](5/16in)  !NOZZLE Width
137     DATA 18,21,22,22           ![mm] H(I)
138     DATA 38.                  ![mm] Xexit
139 END IF
140 Q=1
141 !-----
142 ! LOADING THERMOCOUPLE VOLTAGE-TEMPERATURE
143 ! CONVERSION TABLE
144 PRINT
145 PRINT " LOADING DATA FROM VTconv"
146 ASSIGN @Vtct TO "VTconv"
147 ENTER @Vtct,Tmin,Tmax,Vtable(*)
148 !-----
149 ! CASE NUMBER CONTROL
150 !
151 PRINT USING ""NEXT CASE IS """,3D";Q
152 PRINT " PRESS <CONTINUE> OR ENTER THE"
153 PRINT " CASE NUMBER FROM WHICH YOU WANT TO"
154 PRINT " START"
155 Ivar=0
156 INPUT Ivar
157 IF Ivar>0 AND Ivar<500 THEN
158     Q=Ivar
159 END IF
160 !-----
161 ! COMPUTE STANDARD AIR DENSITY
162 Dspt=14.7*144/53.34/530 ! [Lb/Cu.Ft]
163 ! (spt STANDS FOR "STANDARD PRESSURE AND
164 ! TEMPERATURE")
165 !+++++
166 !
167 ! SETTING DAY AND TIME
168 !
169 Month$=" "

```

```

178 ALPHA OFF
180 PRINT CHR$(12)      ! CLEAR SCREEN
181 PRINT USING """"CASE NO.""",DDD";Q
182 PRINT "ENTER TEST DATE IN THE SPECIFIED FORMAT."
183 PRINT
184 PRINT "PRESS 'CONTINUE' IF THE DATE IS NOT DESIRED"
185 ALPHA ON
187 INPUT "ENTER: MONTH, DAY, YEAR ",Month$,Day$,Year$
188 Hour=0
189 ALPHA OFF
191 PRINT CHR$(12)      ! CLEAR SCREEN
192 PRINT "ENTER TIME OF DAY IN THE SPECIFIED FORMAT."
193 PRINT
194 PRINT "PRESS 'CONTINUE' IF THE TIME IS NOT DESIRED."
195 ALPHA ON
197 INPUT "ENTER: HOURS,MINUTES,SECONDS,'AM' OR 'PM'",Hour,Min,Sec,D$
198 IF Hour<>0 THEN
199   Reftime=TIMEDATE-(Hour*3600+Min*60+Sec)
200   IF Hour>11 THEN Flag1=1
201   D1$=D$
202   IF D$="AM" THEN
203     D2$="PM"
204   ELSE
205     D2$="AM"
206   END IF
207 END IF
234 !-----
235 ! INJECTION TUBE DIMENSIONS
236 Flag6=1      ! PRINT INITIAL MESSAGE.
237 GRAPHICS OFF
238 ALPHA OFF
240 PRINT CHR$(12)
241 PRINT USING """"CASE NO.""",DDD";Q
242 PRINT " INJECTION TUBE DIMENSIONS "
243 PRINT
244 PRINT " Dit      INJECTION TUBE DIAMETER"
245 PRINT " (1)      AT THE THROAT"
246 PRINT " (2)      EXTERIOR AT I.T.E.P."
247 PRINT " (3)      INTERIOR AT I.T.E.P."
248 PRINT
249 FOR J=1 TO 3
250 PRINT USING """" D("","D,"")= """,D.5D,"" mm      """;J,Dit(J)
251 NEXT J
252 !
253 ALPHA ON
255 IF Flag6=1 THEN ! INITIAL MESSAGE
256 PRINT
257 PRINT " ENTER <1> IF MODIFICATIONS ARE DESIRED"
258 PRINT
259 PRINT " PRESS <CONTINUE> FOR NO MODIFICATIONS"
260 Iflag=0

```

```

261     INPUT Iflag
262     IF Iflag<>1 THEN 288
263         Flag6=0
264         GOTO 268
265     END IF
266     GOTO 270
267     !
268     FOR I=1 TO 3
269     GOTO 240
270     PRINT
271     PRINT USING "" " ENTER VALUE FOR Dit("",D,"") IN inches"";I
272     PRINT " PRESS <CONTINUE> FOR NO MODIFICATIONS"
273     Var=0
274     INPUT Var
275     IF Var<>0 THEN
276     Dit(I)=Var
277     Flag5=1
278     END IF
279     NEXT I
280     GOTO 236
281     !-----
282     ! INJECTION TUBE LENGTH
283     ALPHA OFF
284     PRINT CHR$(12)
285     PRINT "INJECTION TUBE EXIT SECTION"
286     PRINT "DISTANCE FROM THROAT:"
287     PRINT USING "" " Xexit = "",DD.DD,"" mm"";Xexit
288     PRINT "ENTER <1> TO MODIFY VALUE"
289     PRINT "OR <CONTINUE> TO KEEP IT"
290     ALPHA ON
291     I=0
292     INPUT I
293     IF I=1 THEN
294     INPUT "ENTER NEW VALUE",Xexit
295     GOTO 288
296     END IF
297     !-----
298     ! NOZZLE VERTICAL DIMENSION AT EACH
299     ! PRESSURE PORT
300     L1000: !
301     IF H(1)=0 THEN H(1)=10.    ![mm]
302     IF H(20)=0 THEN H(20)=1.    ![mm]
303     I=1
304     L1002: Ha=H(I)
305     Ixa=I
306     L1004: I=I+1
307     IF H(I)=0 THEN L1004
308     Ixb=I
309     Hb=H(I)
310     Deltah=(Hb-Ha)/(Ixb-Ixa)
311     FOR J=Ixa+1 TO Ixb-1

```

```

319     H(J)=H(J-1)+Deltah
320 NEXT J
321 IF I<20 THEN L1002
322 ALPHA OFF
324 PRINT CHR$(12)
325 PRINT USING """"CASE NO.""",DDD";Q
326 PRINT "NOZZLE SHAPE"
327 PRINT " IX IS THE PORT NUMBER"
328 PRINT " H IS THE NOZZLE VERTICAL DIMENSION"
329 PRINT " AT THE SPECIFIED PORT"
330 PRINT " UNITS FOR H: INCHES"
331 PRINT " VALUES FOR H ARE:"
332 PRINT "          IX          H          IX          H"
333 PRINT "          [mm]         [mm]         [mm]         [mm]"
334 FOR I=1 TO 10
335     PRINT USING "2(7X,2D,5X,2D.2D)";I,H(I),I+10,H(I+10)
336 NEXT I
337 PRINT "PRESS <CONTINUE> IF YOU WANT THESE VALUES"
338 PRINT " OTHERWISE ENTER <1>"
339 ALPHA ON
341 Iflag=0
342 INPUT Iflag
343 IF Iflag=1 THEN
344     FOR I=2 TO 19
345         Hj(I)=0
346     NEXT I
347 L1010: Var1=0
348     INPUT "ENTER: 'I' , 'H(I)'" ,Var1,Var2
349     IF Var1<>0 AND Var2<>0 THEN
350         I=Var1
351         H(I)=Var2
352         Flag5=1
353         GOTO L1010
354     END IF
355     GOTO L1000
356 END IF
357 ALPHA OFF
359 !-----
360 IF Flag5=1 THEN
361     GCLEAR
362     ALPHA OFF
363     GRAPHICS ON
364     FRAME
365     !
366     !
367     ! A. VERTICAL AXIS AND MARKS
368     LORG 8
369     CSIZE 3.5
370     LINE TYPE 1
371     FOR Z=0 TO 1 STEP .1
372     MOVE -10,100*Z

```

```

373 LABEL Z
374 MOVE -10,100*Z
375 DRAW -12,100*Z
376 MOVE 200,100*Z
377 DRAW 202,100*Z
378 NEXT Z
379 LINE TYPE 4
380 DRAW -10,100
381 LINE TYPE 1
382 MOVE -10,0
383 LABEL 0
384 !          PLOT FRAME
385 MOVE -11,0
386 DRAW 200,0
387 DRAW 200,138
388 DRAW -10,138
389 DRAW -10,0
390 !      B. HORIZONTAL AXIS AND MARKS
391 FOR I=1 TO 20
392 MOVE 10*I,-1.5
393 LORG 6
394 LABEL I
395 MOVE 10*I,138
396 LORG 4
397 LABEL I
398 MOVE 10*I,0
399 DRAW 10*I,1
400 MOVE 10*I,138
401 DRAW 10*I,139
402 NEXT I
403 !      C. LABEL FOR HORIZONTAL AXIS
404 MOVE -20,-1.5          !      LOWER ANOTATION
405 LORG 3
406 LABEL "PORT  "
407 MOVE -20,138.5          !      UPPER ANOTATION
408 LORG 1
409 LABEL "PORT  "
410 MOVE -28,50
411 LDIR 90
412 LORG 6
413 LABEL "PRESSURE RATIO (P/P0)"
414 !      D. NOZZLE LOWER BLOCK SHAPE
415 MOVE 10,138-H(1)*.7874
416 FOR I=2 TO 20
417 DRAW I*10,138-H(I)*.7874
418 NEXT I
419 MOVE 10,138-H(1)*.7874
420 IDRAW -5,-2
421 IDRAW -5,-3
422 IDRAW -5,-4
423 IDRAW -5,-5

```

```

424 ! E. NOZZLE HEIGHT INDICATION MARKS
425 ! AND LABELS
426 FOR I=1 TO 20
427 MOVE I*10,100
428 CSIZE 3
429 LORG 1
430 LABEL USING "2D.2D";H(I)
431 MOVE I*10,105
432 DRAW I*10,135-H(I)*.7874
433 CSIZE 3.5
434 LORG 2
435 LABEL ">"
436 NEXT I
437 !
438 ! F. INJECTION TUBE
439 MOVE -10,138-H(1)*.7874/2+1
440 IDRAW 20+Xexit*10/Tapsep,0
441 IDRAW 0,-2
442 IDRAW -(20+Xexit*10/Tapsep),0
443 ! G. PLOT DEFAULTS
444 LDIR 0
445 LORG 5
446 CSIZE 1.2
447 MOVE -10,100
448 LABEL "O"
449 GSTORE Graph(*)
450 GSTORE Allplot(*)
451 ! STORE DATA IN DISK
452 CALL Datagraph(1)
453 ELSE
454 CALL Clrplt
455 ALPHA OFF
456 GRAPHICS ON
458 END IF
459 IF Flag2=1 THEN 472
460 Flag2=1
461 !
462 !+++++
463 !
464 Scv: CALL Scvrst ! SCANIVALVE RESET
465 !+++++
466 !
467 ! DATA AQUISITION AND CONTROL
468 !
471 IF Flag=0 THEN 559
472 Pmdc: OUTPUT 709;"AC42"
473 ENTER 709;Zero
474 Pzero2=Zero/Kpt2
476 ALPHA OFF
477 PRINT CHR$(12)
478 PRINT USING ""CASE NO."" ,DDD";Q

```

```

479 PRINT USING """"ERROR IN PRESSURE IS""",2D.4D,X,"""bar""";Pzero2
480 OUTPUT 709;"AC43" !CHECK FOR MAGNETIC
481 ENTER 709;Vmf !FEEDER CONDITION.
482 IF Vmf>2 THEN
483 PRINT " MAGNETIC FEEDER ON"
484 ELSE
485 PRINT " MAGNETIC FEEDER OFF"
486 END IF
487 PRINT "ENTER:"
488 PRINT " <0> TO EXIT"
489 PRINT " <1> TO ENTER BAROMETRIC PRESSURE"
490 PRINT " <2> TO ALTER SCANIVALVE SETTINGS"
491 PRINT " <3> TO ALTER TEMPERATURE MEASURING PARAMETERS"
492 PRINT " <4> TO CHECK FOR ZERO READING"
493 PRINT " <5> TO PRINT PRESSURE DIAGRAM"
494 PRINT " <6> TO TURN MAGNETIC FEEDER ON"
495 PRINT " <7> TO TURN MAGNETIC FEEDER OFF"
496 PRINT " <8> TO ALTER PRESSURE DIAGRAM"
497 PRINT " <9> TO CHANGE PLOT SIZE"
499 PRINT " <11> IF PRINT OUT OF RESULTS IS NOT DESIRED"
500 PRINT " <12> TO PRINT RESULTS"
501 PRINT
502 PRINT "PRESS <ENTER> OR <CONTINUE> TO START"
503 GRAPHICS OFF
504 ALPHA ON
506 Cflag=10 ! CONTROL FLAG
507 INPUT Cflag
508 ALPHA OFF
510 !-----
511 IF Cflag=0 THEN STOP
512 !-----
513 IF Cflag=10 THEN 609 ! START TEST
514 !-----
515 IF Cflag=4 THEN 472 !GOTO Pmdc ZERO READING
516 !-----
517 IF Cflag=8 THEN ! MODIFY PRESSURE DIAGRAM
518 PRINT " ENTER <1> TO MODIFY GRAPHICS"
519 PRINT " PRESS <CONTINUE> TO CLEAR GRAPHICS"
520 Iflag=0
521 INPUT Iflag
522 IF Iflag=1 THEN
523 Flag2=1 !RETURN TO Pmdc
524 Flag5=1
525 GOTO 210
526 END IF
527 PRINT " CLEARING GRAPHICS"
528 GCLEAR
P29 GLOAD Graph(*)
530 END IF
531 !-----
532 IF Cflag=11 THEN Flag4=0

```

```

533  !-----
534  IF Cflag=12 THEN Flag4=1
535  !-----
536  IF Cflag=5 THEN
537      ALPHA OFF
538      GRAPHICS ON
539      LORG 1
540      LDIR 0
541      CSIZE 3.5
542      IF Month$=" " THEN 547
543      !
544      !PRINTING DATE
545      MOVE 0,143
546      LABEL USING ""DATE: "" ,10A,DD,"" ,"" ,2X,8A";Month$,Day,Year$
547      MOVE 120,143
548      PRINTER IS 701
549      PRINT CHR$(12)          ! PAPER FORM FEED
550      PRINTER IS 1
551      DUMP GRAPHICS
552      GOTO 472
553  END IF
554  !-----
555  IF Cflag=6 THEN OUTPUT 709;"A04,1,3000"
556  !-----
557  IF Cflag=7 THEN OUTPUT 709;"A04,1,0"
558  !-----
559  IF Cflag=1 OR Flag=0 THEN
560      ALPHA OFF
562      PRINT CHR$(12)          ! CLEAR SCREEN
563      PRINT USING ""CASE NO."" ,DDD";Q
564      PRINT USING ""BAROMETRIC PRESSURE IS: "" ,4D.2D,"" mm Hg"";Patm1
565      ALPHA ON
567      INPUT "ENTER: BAROMETRIC PRESSURE IN mm Hg",Patm1
568      IF Patm1=0 THEN Patm1=760 !DEFAULT
569      Patm2=Patm1*14.696/760    ! [PSI] (abs.)
570      Patm3=Patm2*.06890      ! [bar] (abs.)
572  END IF
573  !-----
574  IF Cflag=2 OR Flag=0 THEN
575      ALPHA OFF
577      PRINT CHR$(12)
578      PRINT USING ""CASE NO."" ,DDD";Q
579      PRINT "-PRESSURE MEASUREMENT CONTROL PARAMETERS-"
580      PRINT USING ""DWELL TIME PER PORT: "" ,D.2D,"" sec"";Y1
581      PRINT USING ""NUMBER OF SAMPLES PER PORT: "" ,2D";N1
582      PRINT USING ""TIME BETWEEN SAMPLES: "" ,D.2D,"" sec"";S1
583      ALPHA ON
585      INPUT "ENETR: DWELL TIME PER PORT (sec.)",Y1
586      INPUT "ENTER: NUMBER OF SAMPLES PER PORT (10 MAX.)",N1
587      INPUT "ENTER: TIME BETWEEN SAMPLES (sec.)",S1
588      IF N1=0 THEN N1=1          ! DEFAULT

```

```

589 END IF
590 !-----
591 IF Cflag=3 OR Flag=0 THEN
592 ALPHA OFF
594 PRINT CHR$(12)
595 PRINT USING ""CASE NO."" ,DDD";Q
596 PRINT "-TEMPERATURE MEASUREMENT CONTROL PARAMETERS-"
597 PRINT USING ""NUMBER OF SAMPLES PER CHANNEL:"" ,2D";N2
598 PRINT USING ""TIME BETWEEN SAMPLES:"" ,D.2D,"" sec"";S2
599 ALPHA ON
601 INPUT "ENTER: NUMBER OF SAMPLES PER CHANNEL (5 MAX.)",N2
602 INPUT "ENTER: TIME BETWEEN SAMPLES (sec.)",S2
603 IF N2=0 THEN N2=1 ! DEFAULT
604 END IF
605 Flag=1
606 !-----
607 IF Cflag<>10 THEN Pmdc
608 !-----
609 CALL Scvrst ! SCV RESET
610 !*****
611 !
612 ! IV. BEGUINING OF MAIN PROGRAM
613 !
614 !*****
615 ALPHA OFF
617 PRINT CHR$(12)
618 PRINT "BEGINING OF TEST"
619 ALPHA ON
621 Realtime=TIMEDATE-Reftime
622 T=TIMEDATE
623 !-----
624 !
625 ! TEMPERATURE MEASUREMENT
626 !
627 ! I CHANNEL POINT
628 ! 45 45 ICE POINT REF.
629 ! 46 46 ROTAM. SEC. AIR
630 ! 47 47 MIXING TANK
631 ! 48 48 ROTAM. PRIM. AIR
632 ! 49 49 STAGN. CHAMBER
633 !
634 PRINT "TEMPERATURE MEASUREMENTS"
636 FOR I=45 TO 49
637 OUTPUT 709;"AC";I
638 FOR J=1 TO N2
639 ENTER 709;Vt(I,J)
640 WAIT S2
641 NEXT J
642 NEXT I
643 !-----
644 !

```

```

645 ! PRESSURE MEASUREMENT
646 !
648 PRINT "PRESSURE MEASUREMENTS"
650 OUTPUT 709;"AC42"
651 FOR I=0 TO 26
652     WAIT Y1 ! DWELL
653     FOR J=1 TO N1 ! READINGS PER PORT
654         WAIT S1 ! DELAY BETWEEN
655             ! SAMPLES
656     ENTER 709;Vp(I,J)
657     NEXT J
658     OUTPUT 709;"TO 1"
659     WAIT .04
660     OUTPUT 709;"TO 0"
661 NEXT I
662 !
663 Time=TIMEDATE-T
664 OUTPUT 709;"AC43" ! CHECK IF MAGNETIC
665 ENTER 709;Vmf ! FEEDER WAS WORKING
667 PRINT "END OF TEST"
668 !*****
669 !
670 ! END OF MAIN PROGRAM
671 !
672 !*****
673 ! TEMPERATURE COMPUTATIONS
674 !
675 FOR I=45 TO 49 ! TAKING AVERAGE OF
676     Sum=0 ! OF VOLTAGES AND
677     FOR J=1 TO N2 ! CONVERTING RESULTS
678         Sum=Sum+Vt(I,J) ! TO MILLIVOLTS
679     NEXT J
680     Vavg(I)=Sum/N2
681     Vref(I)=(Vavg(I)-Vavg(45))*1000. ![mV]
682 NEXT I
683 !
684 ! TRANSFORM VOLTAGE TO TEMPERATURE (Deg.R)
685 FOR I=45 TO 49
686     Temp(I)=FNVt(Vref(I),"R") ![Deg.R]
687 NEXT I
688 !*****
689 ! PRESSURE COMPUTATIONS
690 !
691 Sum=0 ! AVERAGING THE ERROR
692 FOR J=1 TO N1 ! DUE TO ZERO SETTING
693     Sum=Sum+Vp(0,J) ! OF THE SCANIVALVE
694 NEXT J
695 Zero=Sum/N1
696 !-----
697 FOR I=26 TO 1 STEP -1 ! TAKING AVERAGE OF
698     Sum=0 ! PRESSURE,CONVERSION

```

```

699     FOR J=1 TO N1           ! OF UNITS TO PSIA,
700         Sum=Sum+Vp(I,J)    ! AND COMPUTING
701     NEXT J                 ! PRESSURE RATIOS
702     !
703     !     TRANSFORM VOLTAGE TO PRESSURE (PSIA)
704     P(I)=(Sum/N1-Zero)/Kpt1+Patm2
705 NEXT I
706 FOR I=1 TO 26
707     Pr(I)=P(I)/P(24)
708 NEXT I
709 FOR I=25 TO 26
710     Pr2(I)=P(I)/P(22)
711 NEXT I
712 !+++++
713 !     COMPUTING TIME AND DATE OF TEST
714 !
715 IF Hour=0 THEN 730
716 Hour=INT(Realtime/3600)
717 Min=INT(Realtime/60-Hour*60)
718 Sec=INT(Realtime-Min*60-Hour*3600)
719 IF Hour>12 THEN
720     Hour=Hour-12
721     Reftime=Reftime+12.*3600.
722     Flag1=0
723 END IF
724 IF Hour>11 AND Flag1=0 THEN
725     Flag1=1
726     IF D$="PM" THEN Day=Day+1
727     D$=D2$
728     D2$=D1$
729     D1$=D$
730 END IF
731 !+++++
732 !
733 !     -MASS FLOW RATE COMPUTATIONS-           !
734 !
735 PRINTER IS 1
736 ! -MASS FLOW RATE OF SOLIDS
737 PRINT CHR$(12)
738 PRINT USING """"CASE NO.""",DDD";Q
739 PRINT "  MASS FLOW RATE OF SOLIDS IS"
740 PRINT USING """"Dmp=""",4D.3D,"" g/s""";Dmp
741 PRINT "  ENTER THE SOLIDS MASS FLOW RATE IN [g/s]"
742 PRINT "  OR PRESS <CONTINUE> TO KEEP SAME VALUE"
743 Var=0
744 INPUT Var
745 IF Var<>0 THEN
746     Dmp=Var
747 GOTO 739
748 END IF
749 ! -MASS FLOW RATE OF PRIMARY AND SECONDARY

```

```

753 ! AIR.
754 ! BY DEFINITION,
755 ! (MASS FLOW RATE)=(VOL.FLOW RATE)*(DENSITY)
756 ! IN THIS CALCULATIONS, THE MASS FLOW RATE WILL BE
757 ! COMPUTED BY THE USE OF THE EQUATION:
758 !  $Dm_{gx} = Q_{sgx} * D_{spt}$ 
759 !
760 ! WHERE:
761 !  $Dm_{gx}$  IS THE MASS FLOW RATE OF
762 ! THE GAS "X".
763 !
764 !  $Q_{sgx}$  IS THE STANDARD VOLUMETRIC
765 ! FLOW RATE. THAT IS, THE
766 ! VOLUMETRIC FLOW RATE OF THE
767 ! GAS AS IF IT WERE BROUGHT
768 ! TO STANDARD CONDITIONS OF
769 ! PRESSURE AND TEMPERATURE
770 ! (SPT).
771 !
772 !  $D_{spt}$  IS THE STANDARD DENSITY
773 ! OF THE GAS OR THE DENSITY
774 ! WHEN THE GAS IS AT S.P.T.
775 ! CONDITIONS (14.7 PSIA,
776 ! 70 Deg.F).
777 !
778 ! THE STANDARD VOLUMETRIC FLOW RATE
779 ! CAN BE COMPUTED WHEN THE PRESSURE,
780 ! TEMPERATURE AND AIR EQUIVALENT OF THE
781 ! FLOWING GAS ARE KNOWN.
782 !  $Q_{sgx} = Q_{aegx} * \sqrt{P_o/P_s * T_s/T_o}$ 
783 ! WHERE:
784 !  $Q_{aegx}$  IS THE AIR EQUIVALENT
785 ! OF THE FLOWING GAS
786 !
787 !  $P_o$  IS THE OPERATING PRESSURE
788 !  $T_o$  IS THE OPERATING TEMPERATURE
789 !
790 !  $P_s$  IS THE STANDARD PRESSURE
791 !  $T_s$  IS THE STANDARD TEMPERATURE
792 !
793 ! ++++++
794 !
795 ! VOLUMETRIC FLOW RATE READINGS
796 !
797 ! ++++++
798 ALPHA OFF
799 PRINT CHR$(12)
800 PRINT " ROTAMETER SPECIFICATIONS:"
801 PRINT
802 PRINT "PRIMARY AIR ROTAMETER"
803 PRINT " SERIAL: X61-4037/1"

```

```

805 PRINT " AIR EQUIVALENT: 174. S.C.F.M."
806 PRINT " (MET. @14.7 PSIA, 70 Deg.F)"
807 PRINT " SCALE: 31 = 174 S.C.F.M."
808 PRINT
809 PRINT "SECONDARY AIR ROTAMETER"
810 PRINT " SERIAL: X4-4023/1"
811 PRINT " AIR EQUIVALENT: 4.6 S.C.F.M."
812 PRINT " (MET. @14.7 PSIA, 70 Deg.F)"
813 PRINT " SCALE: 100%= 4.6 S.C.F.M."
814 PRINT
815 PRINT " ENTER THE ROTAMETER READINGS AS"
816 PRINT " INDICATED BY THE SCALE"
817 PRINT " IF SAME AS LAST VALUE PRESS <CONTINUE>"
818 ALPHA ON
820 INPUT "ENTER PRIMARY AIR ROTAMETER READING",Qig1
821 INPUT "ENTER SECONDARY AIR ROTAMETER READING",Qig2
822 ALPHA OFF
824 PRINT CHR$(12)
825 PRINT USING "" PRIMARY AIR ROTAMETER READING IS :"" ,4D.3D";
Qig1
826 PRINT
827 PRINT USING "" SECONDARY AIR ROTAMETER READING IS: "" ,4D.3D";
Qig2
828 PRINT
829 PRINT " IF VALUES ARE CORECT, PRESS <CONTINUE>"
830 PRINT " ENTER <1> IF VALUES NEED TO BE MODIFIED"
831 Var=0
832 ALPHA ON
834 INPUT Var
835 IF Var=1 THEN 800
836 !
837 ! THE AIR EQUIVALENT IS COMPUTED WITH
838 ! THE EQUATION:
839 !  $Q_{aegx} = Q_{igx} * SCF$ 
840 !
841 ! WHERE:
842 !  $Q_{igx}$  IS THE INDICATED VOLUMETRIC
843 ! FLOW RATE BY THE ROTAMETER
844 ! SCALE.
845 !
846 ! SCF IS THE SCALE CORRECTION
847 ! FACTOR.
848 !
849  $Q_{aeg1} = Q_{ig1} * (174/31)$  ! AIR EQ. @ SPT
850  $Q_{aeg2} = Q_{ig2} * (4.6/100)$  ! AIR EQ. @ SPT
851 !
852 ! NOTE: THE PRIMARY AIR ROTAMETER SCALE
853 ! READS GALLONS PER MINUTE OF WATER
854 ! WHICH HAS TO BE CONVERTED TO
855 ! S.C.F.M. OF AIR EQUIVALENT.
856 ! THE MAXIMUN FLOW ,31 G.P.M.,

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```

857 !           CORRESPONDS TO 174 S.C.F.M.
858 !           IN A SCALE METERED AT STANDARD
859 !           CONDITIONS (14.7 PSIA, 70 Deg.F,
860 !           AND SPECIFIC GRAVITY 1.)
861 !
862 !           THE SECONDARY AIR ROTAMETER
863 !           SCALE READS 100% OF FULL SCALE
864 !           WHICH CORRESPONDS TO 4.6 S.C.F.M.
865 !           OF AIR EQUIVALENT METERED AT
866 !           STANDARD CONDITIONS: SP.GR.1.,
867 !           14.7 PSIA, 70 Deg.F.
868 ! -----
869 !           COMPUTE STANDARD VOLUMETRIC FLOW RATE
871 Qsg1=Qaeg1*SQR(P(23)/14.7*530/Temp(48))
872 ! [SCFM]
874 Qsg2=Qaeg2*SQR(P(21)/14.7*530/Temp(46))
875 ! [SCFM]
876 ! -----
877 !           COMPUTE MASS FLOW RATE
878 !
879 !
880 Dmg1=Qsg1*Dcpt ! [Lb/min.]
881 Dmg2=Qsg2*Dcpt ! [Lb/min.]
882 ! -----
883 !           CONVERTING TO METRIC UNITS
884 Dmg1=Dmg1*7.5599 ! [g/s]
885 Dmg2=Dmg2*7.5599 ! [g/s]
886 FOR I=1 TO 30
887   P(I)=P(I)*.06890 ! [bar]
888 NEXT I
889 FOR I=46 TO 49
890   Temp(I)=Temp(I)/1.8 ! [K]
891 NEXT I
892 !           PRINT RESULTS
893 CALL Print(Flag4,Q)
894 CALL Plotsub
895 Q=Q+1
896 GOTO Scv
897 END
898 !
899 !
900 !
901 !
902 !
903 !
904 !           VOLTAGE TO TEMPERATURE CONVERSION
905 !
906 DEF FNVt(Vdat,Degree$)
907   INTEGER T,Deltat,Ta,Tb,Tlast
908   COM /Vt/ INTEGER Tmin,Tmax,REAL V(-273:890)
909   !           CHECK IF Vdat IS OUT OF RANGE.
910   IF Vdat>V(Tmax) OR Vdat<V(Tmin) THEN
911     PRINT "      THERMOCOUPLE VOLTAGE"
912     PRINT "      OUT OF TABLE RANGE"
913     PRINT USING "" Vdat="",3D.3D,"" mV"";Vdat

```

```

914 PRINT USING "    " V(Tmin)=" ",3D.3D," mV";V(Tmin)
915 PRINT USING "    " V(Tmax)=" ",3D.3D," mV";V(Tmax)
916 STOP
917 END IF
918 !
919 ! DETERMINE AN ESTIMATE FOR THE VALUE OF
920 ! THE TEMPERATURE.
921 Ta=Tmin+(Tmax-Tmin)*(1/3)
922 Tb=Tmax-(Tmax-Tmin)*(1/3)
923 T=(Tb-Ta)/(V(Tb)-V(Ta))*(Vdat-V(Ta))+Ta
924 IF T>Tmax THEN
925     T=Tmax
926 END IF
927 IF T<Tmin THEN
928     T=Tmin
929 END IF
930 IF V(T)>Vdat THEN
931     Deltat=-1
932 ELSE
933     Deltat=+1
934 END IF
935 Tlast=T
936 T=T+Deltat
937 IF Deltat>0 THEN
938     IF V(T)<Vdat THEN 935
939     Tb=T
940     Ta=Tlast
941 ELSE
942     IF V(T)>Vdat THEN 935
943     Ta=T
944     Tb=Tlast
945 END IF
946 Temp=(Tb-Ta)/(V(Tb)-V(Ta))*(Vdat-V(Ta))+Ta
947 IF Degree$="K" THEN
948     Temp=Temp+273.15
949 END IF
950 IF Degree$="R" THEN
951     Temp=(Temp+273.15)*1.8
952 END IF
953 IF Degree$="F" THEN
954     Temp=1.8*Temp+32
955 END IF
956 RETURN Temp
957 FNEND
958 !
959 ! SCANIVALVE RESET SUBROUTINE
960 SUB Scvrst
961 INTEGER I
962 PRINTER IS 1
963 L10: PRINT CHR$(12)
964 OUTPUT 709;"AC41"

```

```

965  GRAPHICS OFF
966  ALPHA ON
967  PRINT
968  PRINT "SCANIVALVE IS BEING RESET."
969  PRINT "PLEASE WAIT"
970  I=1
971  L15:  ENTER 709;B
972      I=I+1
973  IF I>50 THEN L20
974  IF B<1 THEN      ! CHECK FOR HOME
975  OUTPUT 709;"TO1"  !   POSITION.
976  WAIT .04
977  OUTPUT 709;"TO0"
978  GOTO L15
979  END IF
980  SUBEXIT
981  L20:  PRINT
982  PRINT " SCV RESETING SYSTEM IS NOT WORKING"
983  PRINT " CHECK SCANIVALVE CONNECTIONS"
984  PRINT
985  PRINT "  PRESS <CONTINUE> TO CONTINUE"
986  PAUSE
987  GOTO L10
988  SUBEND
989  !
990  !
991  SUB Plotsub
992  !  THIS SUBROUTINE PLOTS A PRESSURE LINE
993  OPTION BASE 1
994  COM /B14/ REAL P(1:48),Pr(1:48)
995  ALPHA OFF
996  GRAPHICS ON
997  CSIZE 1
998  LORG 5
999  LDIR 0
1000  MOVE -10,100
1002  FOR I=1 TO 20
1003      DRAW 10*I,100*Pr(I)
1004      LABEL "O"
1005      MOVE 10*I,100*Pr(I)
1006  NEXT I
1007  SUBEND
1008  !
1009  SUB Datagraph(INTEGER Flag1) ! LOAD-PLOT
1010  COM /B11/ REAL Dit(1:3),Width
1011  COM /B12/ REAL H(1:20)
1012  COM /B13/ REAL Xexit
1013  COM /B21/ INTEGER Graph(1:7500)
1014  ASSIGN @Path3 TO "GDIgDAT"
1015  IF Flag1=0 THEN
1016  PRINT "  LOADING DATA FROM GDIgDAT"

```

```

1017 PRINT
1018 ASSIGN @Path3 TO "GDIgDAT"
1019 ENTER @Path3;Graph(*)
1020 ENTER @Path3;Dit(*),Width,Q
1021 ENTER @Path3;Xexit
1022 ENTER @Path3;H(*)
1023 ELSE
1024 PRINT " STORING DATA IN GDIgDAT"
1025 PRINT
1026 OUTPUT @Path3;Graph(*)
1027 OUTPUT @Path3;Dit(*),Width,Q
1028 OUTPUT @Path3;Xexit
1029 OUTPUT @Path3;H(*)
1030 END IF
1031 SUBEND
1032 !
1033 SUB Clrplt
1034 COM /B21/ INTEGER Graph(1:7500)
1035 PRINT
1036 PRINT " ERRASING PLOTS"
1037 GLOAD Graph(*)
1038 SUBEND
1039 !
1040 SUB Print(INTEGER Flag4,Case)
1041 COM /B10/ REAL Qig1,Qig2
1042 COM /B14/ REAL P(1:48),Pr(1:48)
1043 COM /B15/ REAL Dmg1,Dmg2,Dmp
1044 COM /B16/ REAL Temp(45:49)
1045 COM /B18/ Month$(10),Day,Year$(5)
1046 COM /B19/ Hour,Min,Sec,D$(2)
1047 COM /B20/ REAL Patm1,Patm2,Patm3
1048 COM /B23/ REAL Time
1049 COM /B25/ REAL Pr2(25:26)
1050 ! PRINT TABLE
1051 IF Flag4=1 THEN
1052 PRINTER IS 701
1053 ELSE
1054 PRINTER IS 1
1055 END IF
1056 PRINT CHR$(12)
1057 PRINT USING "10X, ""TIME: "" ,2Z, "" : "" ,2Z, "" : "" ,2Z,X,2A";Hour,
Min,Sec,D$
1058 IF Month$=" " THEN Prtest
1059 PRINT USING "10X, ""DATE: "" ,10A,DD, "" , "" ,2X,8A";Month$,Day,Year$
1060 Prtest: ! PRINT TEST NO.
1061 PRINT USING "10X, ""CASE No. "" ,3D";Case
1062 PRINT USING "10X, ""ATMOSPHERIC PRESSURE: ""
1063 PRINT USING "10X,4D.2D,X, ""mmHg OR "" ,2D.4D, "" bar "" ;Patm1,
Patm3
1064 PRINT USING "10X,65( "" = "" )"
1065 PRINT USING "10X, ""MIXING TANK/INJECTION TUBE ""

```

```

1066 PRINT USING "10X, ""PORT "" , 7X, ""PRESSURE"" , 6X, "" P/Psc  ""
1067 PRINT USING "28X, ""[bar]""
1068 PRINT USING "16X, 2A, 8X, 3D.3D, 9X, D.3D"; "MT", P(22), Pr(22)
1069 FOR I=25 TO 26
1070 PRINT USING "16X, 2D, 8X, 3D.3D, 9X, D.3D"; I, P(I), Pr(I)
1071 NEXT I
1072 PRINT USING "10X, 65( ""="" )"
1073 PRINT USING "10X, ""NOZZLE""
1074 PRINT USING "15X, ""PORT "" , 7X, ""PRESSURE"" , 6X, "" P/Psc  ""
1075 PRINT USING "28X, ""[bar]""
1076 FOR I=1 TO 20
1077 PRINT USING "16X, 2D, 8X, 3D.3D, 9X, D.3D"; I, P(I), Pr(I)
1078 NEXT I
1079 PRINT USING "10X, 65( ""="" )"
1080 PRINT USING "10X, ""INJECTION TUBE DATA""
1081 PRINT USING "15X, ""PORT "" , 5X, ""PRESSURE"" , 8X, "" P/Pmt.  ""
1082 PRINT USING "26X, ""[bar]""
1083 FOR I=25 TO 26
1084 PRINT USING "16X, 2D, 8X, 3D.3D, 9X, D.3D"; I, P(I), Pr2(I)
1085 NEXT I
1086 PRINT USING "10X, 65( ""="" )"
1087 !
1088 PRINT USING "26X, ""PRIMARY AIR: (GAS 1)          SECONDARY AIR:
(GAS 2)""
1089 PRINT
1090 PRINT USING "15X, ""SECTION:  ROTAMETER  STAGNATION
ROTAMETER  MIXING""
1091 PRINT USING "26X, ""DISCHARGE  CHAMBER  DISCHARGE
TANK""
1092 !
1093 PRINT USING "10X, ""PRESSURE  "" , 2(4X, 2(2D.3D, 5X))"; P(23),
P(24), P(21), P(22)
1094 PRINT USING "10X, ""[bar]""
1095 !
1096 PRINT USING "10X, ""TEMPERATURE  "" , 2(4X, 2(4D.D, 5X))"; Temp(48),
Temp(49), Temp(46), Temp(47)
1097 !
1098 PRINT USING "10X, ""[K]""
1099 PRINT USING "10X, ""MASS FLOW  "" , 3X, 5D.D, 20X, 4D.2D"; Dmg1, Dmg2
1100 PRINT USING "10X, ""[g/s]""
1101 PRINT USING "10X, ""ROT.  READING"" , 3X, 4D.2D, 20X, 4D.2D"; Qig1, Qig2
1103 PRINT USING "10X, 65( ""="" )"
1104 PRINT USING "10X, ""SOLIDS FLOW RATE: "" , 3D.D, "" g/s""; Dmp
1105 PRINT
1106 PRINT USING "10X, ""ELAPSED MEASSURING TIME: "" , 2D.2D, "" s"";
DROUND(Time, 4)
1107 SUBEND

```

```

10      !   VOLTAGE-TEMPERATURE CONVERSION TABLE
20      !   PROG. FILE: VTC
30      !   THERMOCOUPLE TYPE "T"
40      !   COPPER Vs. COPPER-NICKEL
50      !   (COPPER-CONSTANTAN)
60      !   TEMPERATURES IN DEGREES C
70      !   REFERENCE JUNCTION AT 0 DEGREES C
80      !
90      !   "OMEGA 1984 COMPLETE TEMPERATURE
100     !     MEASUREMENT HANDBOOK AND ENCYCLOPEDIA"
110     !   PAGE T-45, TABLE IV
120     !
121     !-----
122     !
123     !   THIS PROGRAM MAY DO THE FOLLOWING:
124     !     A.STORE VOLTAGE DATA IN BDAT FILE NAMED
125     !       "VTconv".
126     !     B.RETREIVE DATA FROM SAME DATA FILE AND
127     !       GIVEN A TEST TEMPERATURE, PRINTS
128     !       THE VOLTAGE.
129     !
130     !+++++
131     !
132     PRINTER IS 1
133
134     INTEGER T,Tmin,Tmax
135
136     DIM V(-273:890)      ! (mV)
137
138     Tmin=-110  !(Deg.C)
139     Tmax=149   !(Deg.C)
140
141     PRINT CHR$(12)
142
143     PRINT "   EXECUTING VTC.PROG"
144
145     PRINT "   VOLTAGE TO TEMPERATURE CONVERSION"
146
147     PRINT
148
149     PRINT USING """"   ARRAY: V("",4D,"","",4D,"")""";Tmin,Tmax
150
151     !
152
153     !   ASSIGNING A PATH TO THE BDAT FILE "VTcon"
154
155     ASSIGN @Dat TO "VTconv"
156
157     PRINT "   ENTER '1' FOR DATA STORAGE PROCESS."
158
159     PRINT "   PRESS <CONTINUE> FOR DATA RETREIVING PROCESS."
160
161     N=0
162
163     INPUT N
164
165     IF N=1 THEN
166
167         PRINT
168
169         PRINT USING """"   READING ARRAY: V("",4D,"","",4D,"")""";Tmin,Tmax
170
171         FOR I=Tmin TO Tmax
172
173             READ V(I)
174
175         NEXT I
176
177         PRINT "   STORING DATA ON DISK"
178
179         PRINT "   FILE: <VTconv>"
180
181         OUTPUT @Dat;Tmin,Tmax,V(*)
182
183         PRINT
184
185         PRINT "   READY"
186
187     ELSE
188
189         PRINT "   RETREIVING DATA FROM DISK"
190

```

```

195 PRINT " FILE: <VTconv>"
197 ENTER @Dat;Tmin,Tmax,V(*)
199 INPUT "ENTER TEST TEMPERATURE (Deg.C)",T
201 PRINT USING "" T="" ,4D,"" Deg.C"" ,4X,""V="" ,3D.3D,""
mV""";T,V(T)
202 GOTO 199
203 END IF
204 !
205 !+++++
210 ! VOLTAGE(mV)
220 !+++++
230 ! T(Deg.C)-->
240 ! ! T
250 ! T T+1 T+2 T+3 T+4
260 ! T+5 T+6 T+7 T+8 T+9
270 !+++++
280 !
290 ! !-110
300 DATA -3.656, -3.629, -3.602, -3.574, -3.547
310 DATA -3.519, -3.491, -3.463, -3.435, -3.407
320 ! !-101
330 !
340 ! !-100
350 DATA -3.378, -3.350, -3.321, -3.293, -3.264
360 DATA -3.235, -3.206, -3.177, -3.147, -3.118
370 ! -91
380 !
390 ! !-90
400 DATA -3.089, -3.059, -3.029, -2.999, -2.970
410 DATA -2.939, -2.909, -2.879, -2.849, -2.818
420 ! !-81
430 !
440 ! !-80
450 DATA -2.788, -2.757, -2.726, -2.695, -2.664
460 DATA -2.633, -2.602, -2.570, -2.539, -2.507
470 ! !-71
480 !
490 ! !-70
500 DATA -2.475, -2.444, -2.412, -2.380, -2.348
510 DATA -2.315, -2.283, -2.250, -2.218, -2.185
520 ! !-61
530 !
540 ! !-60
550 DATA -2.152, -2.120, -2.087, -2.053, -2.020
560 DATA -1.987, -1.953, -1.920, -1.886, -1.853
570 ! !-51
580 !
590 ! !-50
600 DATA -1.819, -1.785, -1.751, -1.717, -1.682
610 DATA -1.648, -1.614, -1.579, -1.544, -1.510
620 ! !41

```

```

630  !
640  !      !-40
650  DATA  -1.475, -1.440, -1.405, -1.370, -1.334
660  DATA  -1.299, -1.263, -1.228, -1.192, -1.157
670  !
680  !
690  !      !-30
700  DATA  -1.121, -1.085, -1.049, -1.013, -.976
710  DATA  -.940, -.903, -.867, -.830, -.794
720  !
730  !
740  !      !-20
750  DATA  -.757, -.720, -.683, -.646, -.608
760  DATA  -.571, -.534, -.496, -.458, -.421
770  !
780  !
790  !      !-10
800  DATA  -.383, -.345, -.307, -.269, -.231
810  DATA  -.139, -.154, -.116, -.077, -.039
820  !
830  !+++++
840  !
850  !      ICE POINT
860  !
870  !+++++
880  !
890  !      ! 0C
900  DATA  .000, .039, .078, .117, .156
910  DATA  .195, .234, .273, .312, .351
920  !
930  !
940  !      ! 10C
950  DATA  .391, .430, .470, .510, .549
960  DATA  .589, .629, .669, .706, .749
970  !
980  !
990  !      ! 20C
1000 DATA  .789, .830, .870, .911, .951
1010 DATA  .992, 1.032, 1.073, 1.114, 1.155
1020 !
1030 !
1040 !      !30 C
1050 DATA  1.196, 1.237, 1.279, 1.320, 1.361
1060 DATA  1.403, 1.444, 1.486, 1.528, 1.569
1070 !
1080 !      !40 C
1090 DATA  1.611, 1.653, 1.695, 1.738, 1.780
1100 DATA  1.822, 1.865, 1.907, 1.950, 1.992
1110 !
1120 !      !50 C
1130 DATA  2.035, 2.078, 2.121, 2.164, 2.207

```

1140	DATA	2.250,	2.294,	2.337,	2.380,	2.424
1150	!					
1160	!	!60 C				
1170	DATA	2.467,	2.511,	2.555,	2.599,	2.643
1180	DATA	2.687,	2.731,	2.755,	2.819,	2.864
1190	!					
1200	!	!70 C				
1210	DATA	2.908,	2.953,	2.997,	3.042,	3.087
1220	DATA	3.131,	3.176,	3.221,	3.266,	3.312
1230	!					
1240	!	!80 C				
1250	DATA	3.357,	3.402,	3.447,	3.493,	3.538
1260	DATA	3.584,	3.630,	3.676,	3.721,	3.767
1270	!					
1280	!	!90 C				
1290	DATA	3.813,	3.859,	3.906,	3.952,	3.998
1300	DATA	4.044,	4.091,	4.137,	4.184,	4.231
1310	!					
1320	!	!100 C				
1330	DATA	4.277,	4.324,	4.371,	4.418,	4.465
1340	DATA	4.512,	4.559,	4.607,	4.654,	4.701
1350	!					
1360	!	!110 C				
1370	DATA	4.749,	4.796,	4.844,	4.891,	4.939
1380	DATA	4.987,	5.035,	5.083,	5.131,	5.179
1390	!					
1400	!	!120 C				
1410	DATA	5.227,	5.275,	5.324,	5.372,	5.420
1420	DATA	5.469,	5.517,	5.566,	5.615,	5.663
1430	!					
1440	!	!130 C				
1450	DATA	5.712,	5.761,	5.810,	5.859,	5.908
1460	DATA	5.957,	6.007,	6.056,	6.105,	6.155
1470	!					
1480	!	!140 C				
1490	DATA	6.204,	6.254,	6.303,	6.353,	6.403
1500	DATA	6.452,	6.502,	6.552,	6.602,	6.652
1510	!					
1520	END					

APPENDIX H

EXPERIMENTAL PRESSURE READINGS ALONG THE INJECTOR

Table H.1. Pressure Readings for Test with Theoretically-Computed Nozzle Contour and Design Values of the Mass Flow Rates

Port No.	Absolute Pressure [bar]	Pressure Ratio (P/P_{gl})
Stag. Chambr.	1.595	1
1	1.158	.726
2	1.118	.701
3	1.136	.713
4	1.161	.728
5	1.149	.721
6	1.136	.712
7	1.122	.703
8	1.106	.694
9	1.095	.987
10	1.083	.679
11	1.069	.671
12	1.054	.661
13	1.039	.652
14	1.025	.643
15	1.010	.633
16	.992	.622
17	.972	.610
18	.952	.597
19	.936	.587
20	.918	.576

Table H.2. Pressure Readings During Test with Overpressurized
Stagnation Chamber and Theoretically-Computed
Cross-Sectional Areas

Port	Absolute Pressure [bar]	Pressure Ratio (P/P_{gl})
Stag. Chambr.	4.394	1
1	2.777	.632
2	1.770	.403
3	1.719	.391
4	2.654	.604
5	2.714	.618
6	2.700	.614
7	2.675	.609
8	2.646	.602
9	2.612	.595
10	2.602	.592
11	2.564	.583
12	2.529	.575
13	2.485	.566
14	2.440	.555
15	2.370	.540
16	2.320	.528
17	2.245	.511
18	2.135	.486
19	2.003	.456
20	1.750	.398

Table H.3. Pressure Readings Corresponding to the Test with a Modified Nozzle Block Contour

Port	Absolute Pressure [bar]	Pressure Ratio (P/P_{gl})
Stag. Chambr.	3.555	1
1	2.302	.648
2	.734	.206
3	.444	.125
4	.526	.148
5	.415	.117
6	.466	.131
7	.405	.114
8	.448	.126
9	.413	.116
10	.436	.123
11	.413	.116
12	.428	.120
13	.407	.115
14	.407	.115
15	.661	.186
16	.792	.223
17	.852	.240
18	.883	.248
19	.906	.255
20	.921	.259

APPENDIX I

UNCERTAINTY ANALYSIS

The analysis is made for the mass flow rate of both primary and secondary air. The experimental value of mass flow rate is computed by the equation

$$\dot{m} = Q_i (SF) \sqrt{\frac{P}{14.7} \frac{530}{T}} D_{spt}$$

where: $\dot{m}$ is the mass flow rate in [lb/min.],

Q_i is the indicated reading in the
rotameter scale [scale units],

(SF) is the scale factor [s.c.f.m./scale unit],

P is the pressure reading at the rotameter
exit [lbf/sq.in.],

T is the temperature reading at the rotameter
exit [°R],

D_{spt} is the density of the air at standard
conditions of pressure and temperature
given by the manufacturer (14.7 psi and
530°R).

This equation can be written as

$$\dot{m} = K_r Q_i \sqrt{\frac{P}{T}}$$

where K_r is a constant for the particular rotameter.

If P is in [bar], T in [°K], and m in [g/s], the constant K_r becomes

$K_1=54.157$ (for primary air rotameter)

and

$K_2=.44384$ (for secondary air rotameter).

If W_q is the uncertainty in the scale reading, W_p is the uncertainty in

the pressure readings, and W_t is the uncertainty in the temperature reading, then the uncertainty in the mass flow rate is

$$W_m = \left[\left(\frac{\partial \dot{m}}{\partial Q_i} W_q \right)^2 + \left(\frac{\partial \dot{m}}{\partial P} W_p \right)^2 + \left(\frac{\partial \dot{m}}{\partial T} W_t \right)^2 \right]^{.5}$$

where:

$$\frac{\partial \dot{m}}{\partial Q_i} = \frac{K_r P}{T}$$

$$\frac{\partial \dot{m}}{\partial P} = \frac{K_r Q_i}{2} \sqrt{\frac{1}{P T}}$$

and

$$\frac{\partial \dot{m}}{\partial T} = - \frac{K_r Q_i}{2} \sqrt{\frac{P}{T^3}}$$

Substituting these expressions gives:

$$W_m = K_r \left[\frac{P (W_q)^2}{T} + \frac{(Q_i)^2 (W_p)^2}{4 P T} + \frac{(Q_i)^2 P (W_t)^2}{4 T^3} \right]^{.5}$$

The uncertainty in pressure is $W_p = .005$ bar and the uncertainty in temperature is $\pm .5^\circ\text{K}$. The uncertainty in scale readings are ± 0.5 scale units for primary air rotameter and 1.0 scale units for secondary air rotameter. Tables D.1 to D.3 contain the results of the uncertainty analysis for mass flow rates of primary and secondary air for the three tests.

The uncertainty in the mass flow rate of solids is $\pm .2$ g/s. This figure was determined after setting the magnetic vibratory feeder at the desired solids flow rate for the experimental test. All physical dimensions are uncertain in a range of $\pm .05$ mm due to instrument precision.

Table I.1. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air and Secondary Air for Test with Theoretically-Determined Contour and Design Values of Mass Flow Rates

	Primary Air	Secondary Air
Static Pressure at Rotameter Discharge [bar]	± 1.698	± 1.462
Static Temperature at Rotameter Discharge [$^{\circ}\text{K}$]	± 294.1	± 294.8
Rotameter Indicated Reading [scale units]	± 11.5	± 27.0
Nominal Mass Flow Rate [g/s]	± 47.3	$\pm .84$
Uncertainty in Mass Flow Rate [g/s] (percent)	± 2.1 (± 4.4)	$\pm .032$ (± 3.81)

Table I.2. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air for Test with Theoretically-Determined Contour and $P_{g1} = 4.394$ bar

	Primary Air
Static Pressure at Rotameter Discharge [bar]	± 4.738
Static Temperature at Rotameter Discharge [$^{\circ}\text{K}$]	± 297.3
Rotameter Indicated Reading [scale units]	± 20.75
Nominal Mass Flow Rate [g/s]	± 141.9
Uncertainty in Mass Flow Rate [g/s] (percent)	± 3.5 (± 2.5)

Table I.3. Pressure, Temperature, Rotameter Readings, Mass Flow Rates, and Uncertainty for Mass Flow Rates of Primary Air and Secondary Air for Test with Modified Channel Contour

	Primary Air	Secondary Air
Static Pressure at Rotameter Discharge [bar]	± 3.610	± 1.130
Static Temperature at Rotameter Discharge [$^{\circ}\text{K}$]	± 296.4	± 296.1
Rotameter Indicated Reading [scale units]	± 8.50	± 30.5
Nominal Mass Flow Rate [g/s]	± 50.7	$\pm .84$
Uncertainty in Mass Flow Rate [g/s] (percent)	± 3.1 (± 5.9)	$\pm .028$ (± 3.3)

APPENDIX J

ESTIMATION OF THE INJECTION PRESSURE

Simple one-dimensional theory of compressible gases is used. The calculations refer to Figure 6.10.

With $\theta_1=37.5^\circ$ and the deflection angle $\delta=2^\circ$, and using oblique shock charts, the Mach numbers before and after the shock can be determined. They are $M_i = 1.72$ and $M_{ii} = 1.625$. The normal component of the Mach vector relative to the first shock at region I is

$$M_i(n) = 1.72 \sin(37.5^\circ) = 1.047 .$$

The static pressure ratio across the shock is determined by using normal shock tables with $M_i(n)=1.047$ as the Mach number upstream of the shock:

$$\frac{P_{ii}}{P_i} = 1.113 .$$

Since P_i is known (P_i is the pressure at port 3), the pressure at region II can be determined:

$$P_{ii} = .444 \text{ bar } (1.113) = .494 \text{ bar} .$$

The pressure at region III can be estimated as a function of the shock angles and it can be compared with the experimental value corresponding to the pressure at port 4. The normal component of the Mach vector relative to the second oblique shock is

$$M_{ii}(n)=1.625 \sin(40^\circ) = 1.045 .$$

Using this result and normal shock tables,

$$\frac{P_{iii}}{P_{ii}} = 1.106 .$$

Finally,

$$P_{iii} = .494 \text{ bar } (1.106) = .546 \text{ bar} .$$

VITA

Jose Angel Lamas is a Venezuelan citizen, although he was born in La Habana, Cuba on November 27, 1957. He grew up in Caracas and attended elementary and high schools at "Colegio Claret". Then, he studied at "Universidad Simon Bolivar" where he received the Bachelor of Science Degree in Mechanical Engineering on May 29, 1981. Afterwards, he continued his studies at the University of Tennessee, Knoxville where he graduated with a Master of Science Degree in Mechanical Engineering on August 29, 1985.