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I am submitting herewith a thesis written by Gregory S. Mailen entitled "The Enhancement of Heat Transfer for Ammonia Evaporating Outside Vertical Tubes." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Mechanical Engineering.

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THE ENHANCEMENT OF HEAT TRANSFER FOR AMMONIA
EVAPORATING OUTSIDE VERTICAL TUBES

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ABSTRACT

Experiments were conducted to determine the heat transfer performance of single vertical tubes with ammonia evaporating from a thin film on the outside of the tube. The three aluminum tubes employed were of 2.54-cm (1-in.) nominal diameter and 1.22-m (4-ft) length: the first tube had smooth inside and outside surfaces; the second one had a smooth inside surface, but 48 flutes on the outside; and the third tube had 34 flutes on the inside and 42 flutes on the outside. Three different ammonia feed rates [$3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm), $6.13 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm), and $15.77 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm)] were used in the tests for each tube, while the heat load was varied from 690 W (2360 Btu/h) to 3990 W (13,620 Btu/h).

Evaporation heat transfer coefficients, based on the total tube outside surface area, are reported as composite coefficients, which include the resistances of both the evaporating film and the tube wall. Composite evaporation heat transfer coefficients ranged from $2720 \text{ W/m}^2\cdot\text{K}$ ($480 \text{ Btu/h ft}^2\cdot^\circ\text{F}$) to $12,020 \text{ W/m}^2\cdot\text{K}$ ($2120 \text{ Btu/h ft}^2\cdot^\circ\text{F}$). In general, the largest heat transfer coefficients were obtained at the highest heat load and ammonia feed rate tested. Corresponding composite temperature differences ranged from 1.3 K (2.3°F) to 5.7 K (10.2°F), while reflux ratios, the ratio of ammonia feed rate to evaporation rate, ranged from 1.1 to 12.6.

A brief photographic study illustrates the presence of boiling during some of the ammonia evaporation test runs. During thin film

evaporation of ammonia, no appreciable heat transfer enhancement was obtained when utilizing fluted surfaces in stead of smooth ones.

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LIST OF SYMBOLS

a_0	y-intercept on the Wilson plot representing the composite resistance of the evaporating film and wall
a_1	slope of the line on the Wilson plot
A	heat transfer surface area of test tube
c_p	specific heat
C_{sf}	constant in Rohsenow correlation (accounts for various liquid-heater surface combinations)
D	tube diameter
F	volume flow rate
g	local gravitational acceleration
g_o	conversion factor, $4.17 \times 10^8 \text{ lb}_m\text{-ft/lb}_f\text{-h}^2$
G	mass flow rate per unit area
h	local heat transfer coefficient
$\bar{h}$	average or mean individual heat transfer coefficient
h_b	boiling heat transfer coefficient
h_c	convection heat transfer coefficient
h_e	evaporation side heat transfer coefficient
h_{fg}	latent heat of vaporization
h_c^*	composite evaporation heat transfer coefficient including both the wall and the evaporating film
k	thermal conductivity
λ	tube length
$\dot{m}$	mass flow rate
Nu	Nusselt number
P_t	outside perimeter of the tube

Subscripts

avg	average
b	bulk, boiling
c	composite, convection
cs	cross section
e	evaporator, evaporation
f	film
fi	inside fouling
fo	outside fouling
h	hydraulic
i	inside
in	inlet
lm	log mean
N	ammonia
o	outside
out	outlet
r	rod
s	saturation
t	total
tr	transition
v	vapor, vapor side
w	water, water side
wall	wall, surface
Pr	Prandtl number
Q	heat load, heat transfer rate
Q/A	heat flux
r	radius

R	resistance to heat flow
Re	Reynolds number
RF	reflux ratio (ratio of feed rate to evaporation rate)
T	temperature
ΔT	temperature difference
$\overline{\Delta T}$	mean temperature difference between heating water and evaporating ammonia film
ΔT_c^*	composite temperature difference including both wall and evaporating film
U	overall evaporation heat transfer coefficient
V	water velocity

Greek Symbols

$\overline{\Gamma}$	average mass flow rate per unit length of periphery
δ	film thickness
Γ	mass flow rate per unit length of tube periphery
α	diffusivity of heat
ϕ	normalizing term, $(k^3 \rho^2 g / \mu^2)^{1/3}$
Δ	finite difference
μ	absolute viscosity
ρ	mass density
σ	surface tension
ν	kinematic viscosity
Σ	summation

1. INTRODUCTION

The present energy crisis has increased interest in the exploitation of alternative energy resources. Renewable resources such as geothermal, solar, and ocean thermal energy are being considered as possible solutions to the dwindling supply and increasing demand for low-cost energy in today's society. Among these possible energy resources, ocean thermal energy conversion (OTEC) is viewed as a very promising alternative.

As early as 1881, d'Arsonval¹ suggested the possibility of closed-cycle OTEC employing ammonia or propane as a working fluid. More recently in 1975, Lockheed Missiles and Space Company, Inc.² and TRW Systems Group³ established separate baseline designs for OTEC power plants in response to a Department of Energy (DOE) initiative; both designs use ammonia as the working fluid in a closed Rankine cycle. The OTEC prototype power station, as envisioned by TRW (Fig. 1.1), houses four 25-MW(e) power generating units in a 17-story reinforced concrete hull. The power station's deck, which is about the size of a football field, may accommodate a manufacturing plant or other OTEC power user. Projected capital costs for an OTEC plant range from \$1200 to \$2100 per kilowatt.

Ammonia has been chosen for the OTEC power cycle because its superior heat transfer characteristics and thermodynamic properties result in a more cost-effective plant, when compared to other candidate working fluids. Also, it is readily available at a modest cost. In the proposed Rankine cycle for OTEC (Fig. 1.2), warm surface seawater, which is

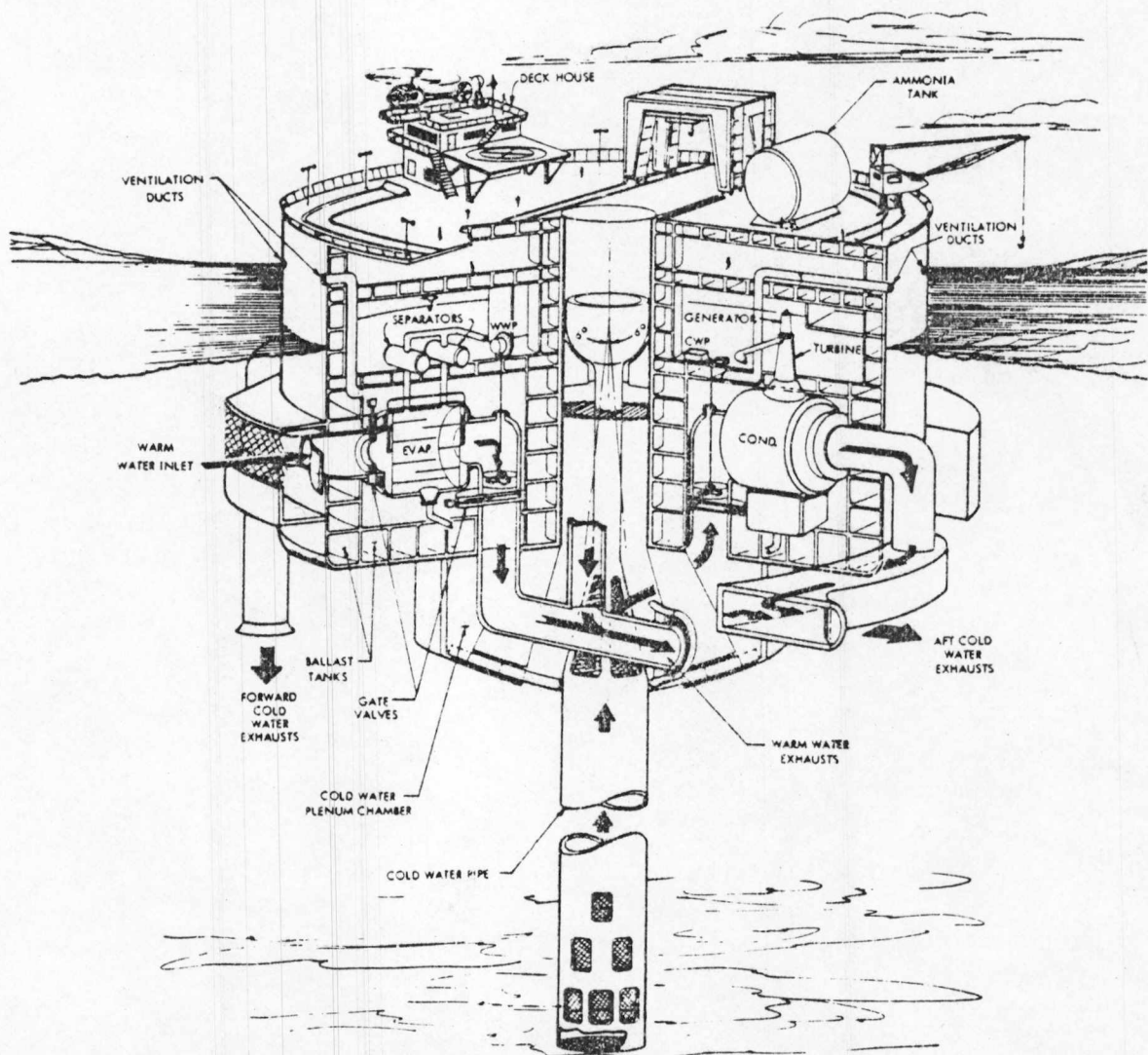


Fig. 1.1. Conceptual baseline design for OTEC plant (TRW Systems Group).

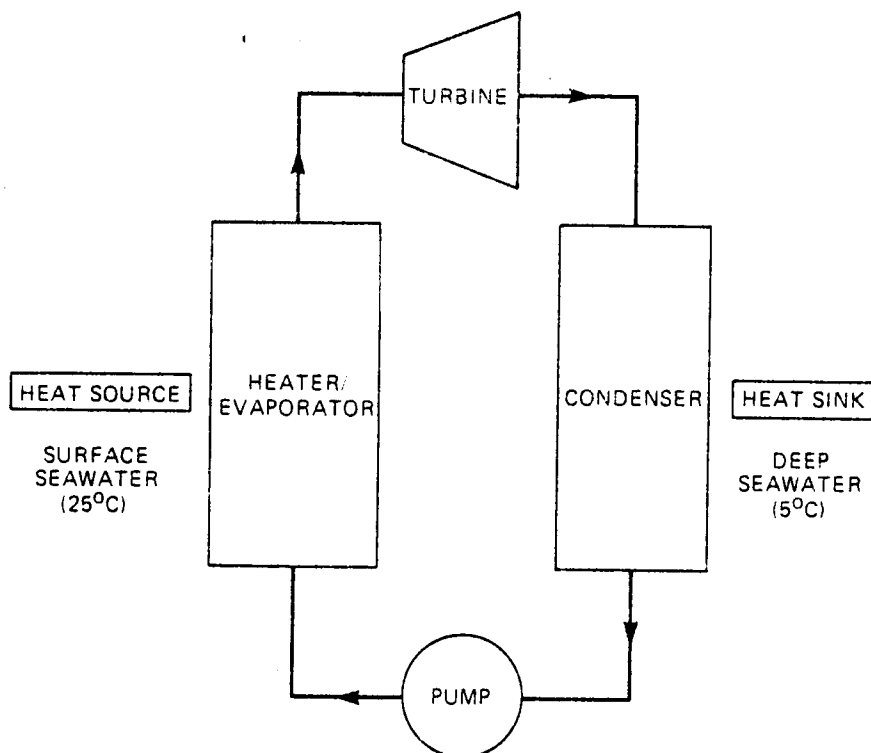


Fig. 1.2. Proposed ammonia Rankine cycle for OTEC.

heated daily by solar radiation, and liquid ammonia are pumped through the evaporator. Ammonia, vaporized in the evaporator, drives a turbine which, in turn, drives a generator. The ammonia exits the turbine at a lower pressure and flows into the condenser, where the cold, deep seawater causes the ammonia to condense. The pump then raises the pressure of the ammonia and returns it to the evaporator, thus completing the cycle.

Depending on the particular site and depth considered for OTEC power plants, typical surface-to-depth temperature differences (ΔT) of seawater are, at most, 17 to 22 K (30 to 40°F). This available temperature difference is small compared to the temperature potential of conventional power plants. Further, from a thermodynamic standpoint, only

a small fraction of this low-temperature heat can be converted to net work. Thus, in a conversion system using a secondary fluid, heat exchangers would be expected to be relatively large and constitute a major part of the total system capital costs. Therefore, improvements in heat exchanger thermal performance can result in substantial cost reductions and will favorably affect the overall feasibility of developing this resource.

One method for increasing the thermal performance of heat exchangers is the use of a modified (fluted) heat transfer surface to enhance the heat transfer coefficients. Gregorig⁴ was the first to analytically describe and report experimental evidence on the effectiveness of the fluted, enhanced surface for significantly augmenting film condensation heat transfer; by fluting the outside surface of a vertical tube in steam condensing applications, average film condensation coefficients may be increased 200 to 800%. Subsequent investigators studying desalination processes — Carnavos⁵ and Alexander and Hoffman⁶ — developed a large body of data for steam condensation and evaporation on fluted surfaces and reported similar enhancements. More recent studies at the Oak Ridge National Laboratory (ORNL) by Combs⁷ and by Combs, Mailen, and Murphy⁸ examined ammonia, fluorocarbons, and a hydrocarbon condensing on several modified tube geometries. Although the magnitude of enhancements varied with fluid properties, tube geometries, and heat fluxes, fluted tubes were found to enhance condensing film coefficients up to 720% over those obtained with a conventional smooth tube.

In a manner similar to earlier ORNL work, the present study examined the potential for improving the heat transfer performance of

evaporators by utilizing fluted surfaces. The need for these studies rests, in large part, on the sparseness of data for fluids other than water evaporating from fluted surfaces. Thin film evaporation is of great interest for OTEC applications, since relatively high heat fluxes can be achieved with small temperature differences by combined boiling and convection heat transfer mechanisms. The emphasis on fluted tubes stemmed from the high performance efficiency identified in water studies such as those of Alexander and Hoffman.⁶ A possible explanation for the evaporation heat transfer enhancements obtained by Alexander and Hoffman⁶ is the wavy-film theory (Fig. 1.3). Wavy-film flow is characterized by the passage of waves down the tube, having a sizable

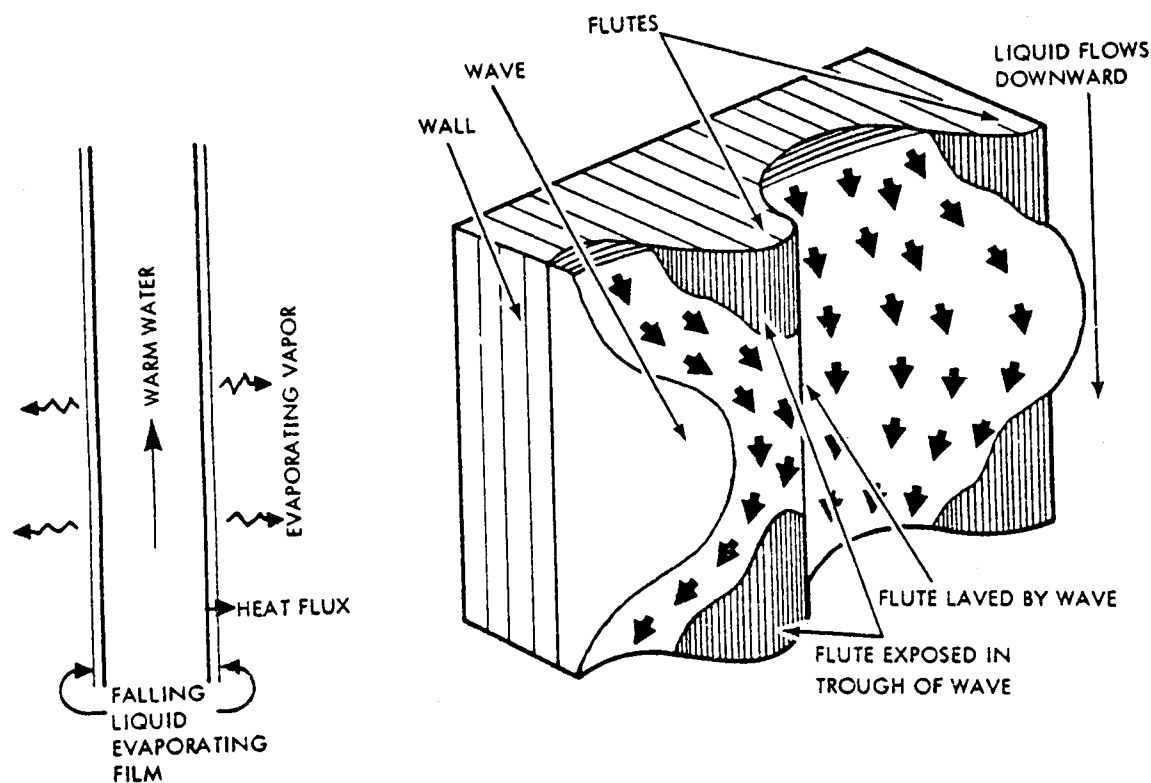


Fig. 1.3. Fluted-tube wavy-film theory for enhancement of evaporation heat transfer coefficients.

thickness compared to the mean thickness of the falling film. These waves periodically wet the flute crests with a thin liquid film, thus promoting heat transfer by evaporation.

The present experimental study includes the determination of composite heat transfer coefficients for a thin film of ammonia evaporating on the vertical outside wall of both smooth and fluted single tubes. Experimental data and results are presented along with a brief photographic study of the ammonia evaporation process.

2. BACKGROUND

To predict the performance of falling film evaporation, it is necessary to know the heat transfer coefficient for nonnucleating conditions in which all evaporation takes place from the film surface; in consequence, essentially all of the heat is conducted through the whole liquid layer. Although data on this kind of heat transfer are not extensive, predictions for laminar flow [Eq. (2.1)] have been based on a correlation by Nusselt:⁹

$$h_{\text{Nusselt}} = \frac{k}{\delta} = \left(\frac{4}{3}\right)^{1/3} \left(\frac{k^3 g}{\nu^2}\right)^{1/3} \left(\frac{4\Gamma}{\mu}\right)^{-1/3}. \quad (2.1)$$

Kutateladze¹⁰ has made modifications to this prediction [Eq. (2.2)] to account for the ripple effect on the film surface. These capillary waves, or ripples, reduce the average film layer thickness for a given flow rate, so that the heat transfer coefficient is increased [Eq. (2.2)]:

$$(\bar{h})_{\text{ripples}} = 0.8 \left(\frac{\Gamma}{\mu}\right)^{0.11} \bar{h}_{\text{Nusselt}}. \quad (2.2)$$

For the turbulent flow regime, theoretical predictions like those of Dukler¹¹ [Eq. (2.3)] have been used to estimate the local heat transfer coefficient:

$$h_c = 3.8 \times 10^{-3} \left(\frac{\nu^2}{k^3 g}\right)^{-1/3} \left(\frac{4\Gamma}{\mu}\right)^{0.4} \left(\frac{\nu}{\alpha}\right)^{0.65}. \quad (2.3)$$

The intersection of correlations in Eqs. (2.2) and (2.3) indicates a departure from the wavy laminar regime at the Reynolds Number:

$$\left(\frac{4\Gamma}{\mu}\right)_{tr} = 5800 \left(\frac{\nu}{\alpha}\right)^{-1.06} . \quad (2.4)$$

Wilke¹² presented results for the heating of falling water films on the exterior of a vertical tube essentially without evaporation. He gave a correlation for turbulent heat transfer coefficients as

$$h = 8.7 \times 10^{-3} \left(\frac{\nu^2}{k^3 g}\right)^{-1/3} \left(\frac{4\Gamma}{\mu}\right)^{0.4} \left(\frac{\nu}{\alpha}\right)^{0.344} , \quad (2.5)$$

valid for $1600 < Re_f < 3200$. These predictions are, at most, approximate, since not enough is known about the nature of the flow to permit an analysis based on the dynamics of the fluid motion itself.

For a forced convective boiling regime, the average heat transfer coefficient may be predicted in a manner similar to that of Bergles and Rohsenow¹³ and presented by Lorenz and Yung:¹⁴

$$\bar{h} = \underbrace{h_b}_{\text{Boiling}} + \underbrace{h_c}_{\text{Convection}} , \quad (2.6)$$

where

$$h_b = \frac{\mu h_{fg}}{C_{sf}^3 (g_0 \sigma / g \rho)} \left(\frac{C_p}{h_{fg} Pr^{1.7}} \right)^3 \Delta T^2 , \quad (2.7)$$

and for turbulent flow

$$h_c = 3.8 \times 10^{-3} \left(\frac{v^2}{k^3 g} \right)^{-1/3} \left(\frac{4\Gamma}{\mu} \right)^{0.4} \left(\frac{v}{\alpha} \right)^{0.65}, \quad (2.3)$$

while for laminar flow

$$h_c = 0.606 \left(\frac{v^2}{k^3 g} \right)^{-1/3} \left(\frac{4\Gamma}{\mu} \right)^{-0.22}. \quad (2.8)$$

This model assumes that the amount of evaporated fluid is small compared to the feed flow rate.

An experimental study was initiated at ORNL to determine the performance of vertical smooth and fluted tubes for ammonia evaporation, and to compare the results obtained with standard correlations. Major components of the OTEC Evaporator-Condenser Test Facility (OTEC-ECTF) are explained in detail in Sect. 3, results from evaporation experiments are presented in Sect. 6, and conclusions are given in Sect. 7.

3. DESCRIPTION OF EQUIPMENT

The OTEC-ECTF used in this investigation is shown in the general flow diagram (Fig. 3.1) and in the overall views presented in Figs. 3.2 through 3.4. Major loop components explained in detail in the following sections include (1) experiment tubes, (2) ammonia reservoir, (3) ammonia pump, (4) entrainment separator, (5) evaporator water storage tank and pump, (6) condenser water storage tank and pump, (7) evaporator module, (8) separator cup, and (9) condenser module. The evaporator and condenser modules were both shell and single tube, counterflow heat exchangers. Water circulating upward inside the tubes served as the heating source for the ammonia in the evaporator module, and as the heat sink in the condenser module.

3.1 General Flow Description

Flow directions are indicated by arrows in the simplified schematic diagram (Fig. 3.5). The experimental system consisted of three primary circuits: an evaporator water (heating) loop, an ammonia circulation loop, and a condenser water (cooling) loop. Three secondary cooling water loops were used for heat removal from each of the primary loops. Demineralized water was circulated through the primary water loops, while process water was used in the secondary loops. The ammonia circulation loop was designed for a maximum operating temperature and pressure of 316 K (110°F) and 1.72×10^6 Pa (250 psia).

Typically, slightly subcooled liquid ammonia [subcooled less than 1.1 K (2.0°F)] was transferred by a canned rotor pump from the ammonia

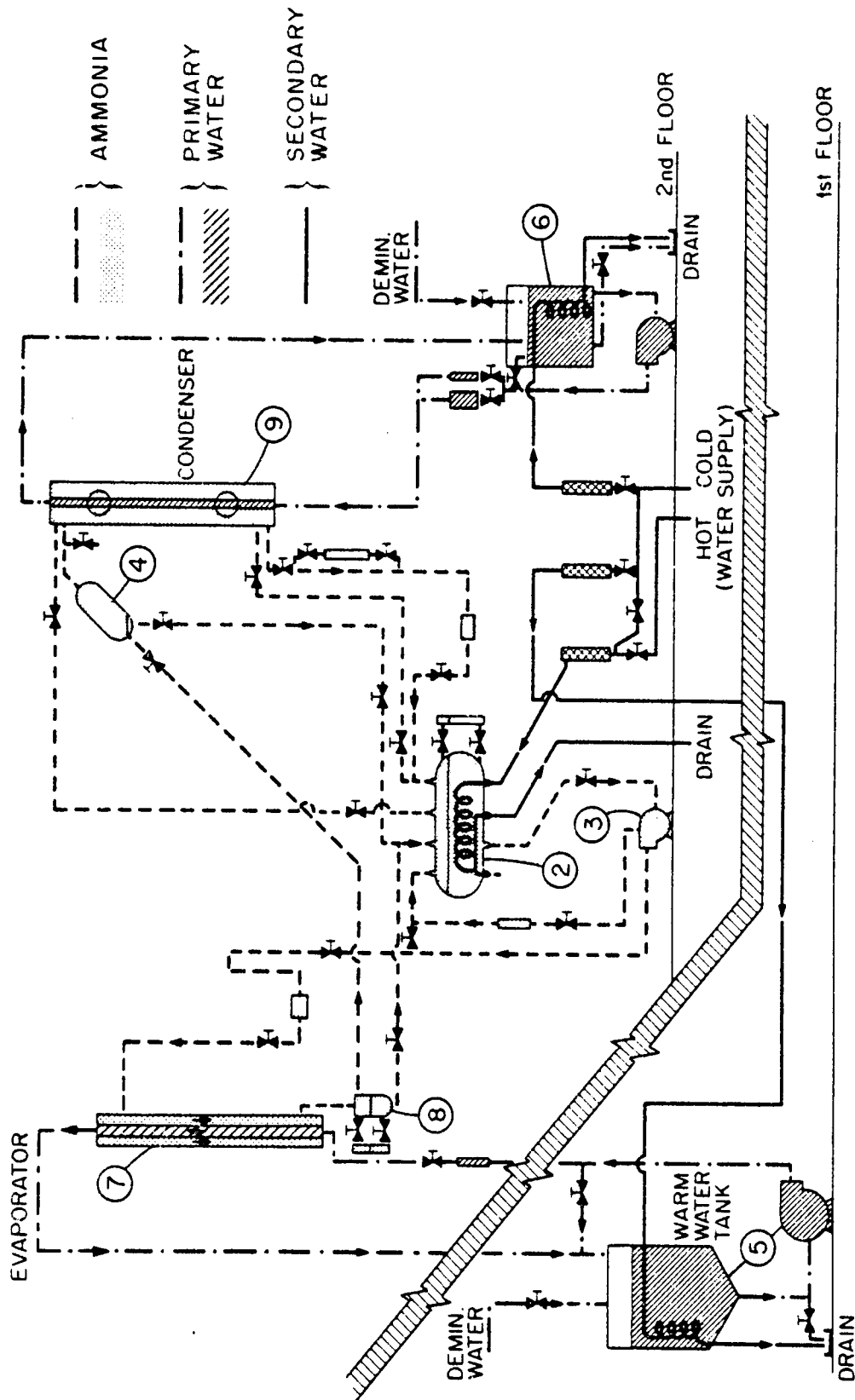


Fig. 3.1. Generalized flow diagram of Ocean Thermal Energy Conversion-Evaporator Condenser Test Facility (OTEC-ECTF).

OTEC-ECTF

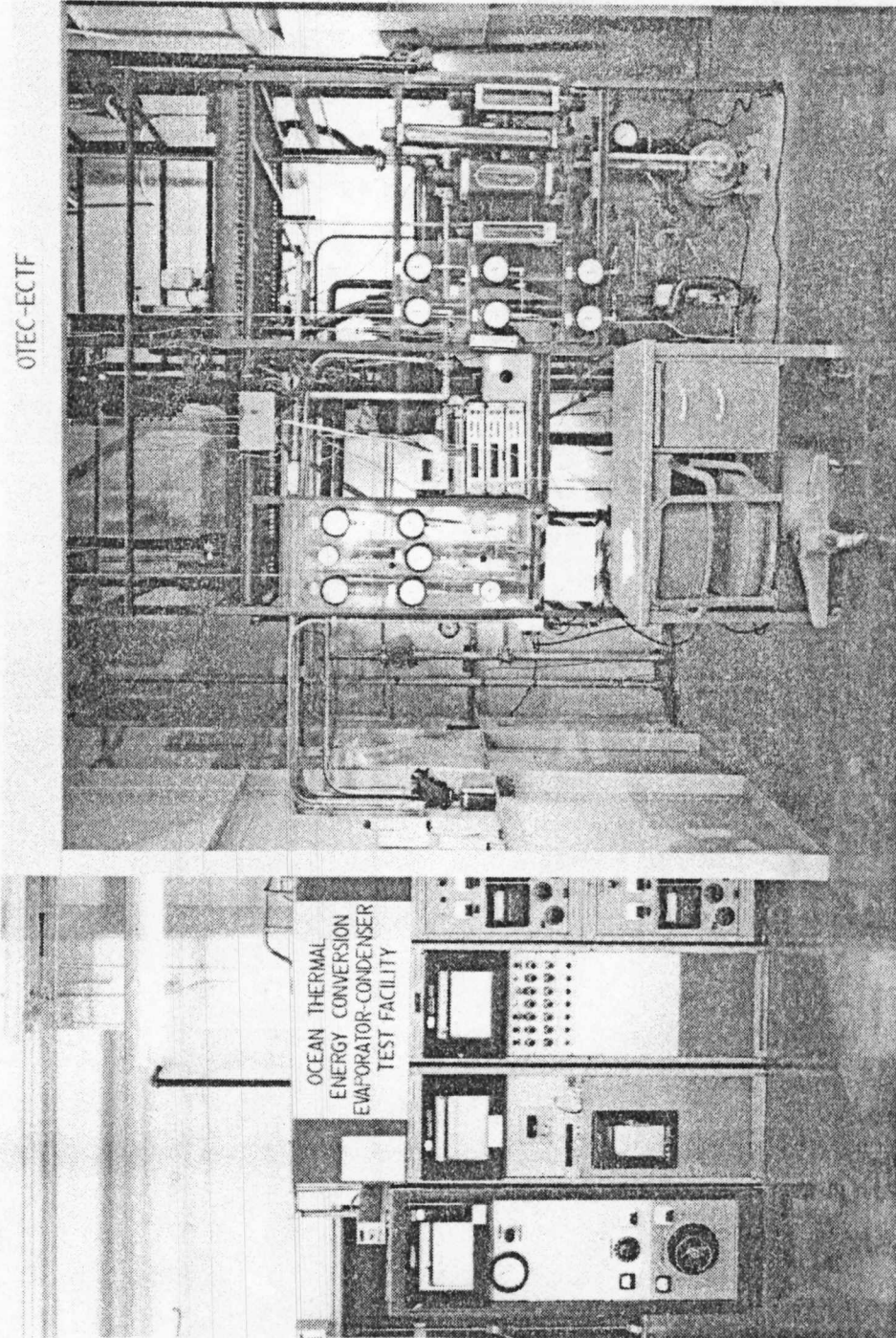


Fig. 3.2. Overall view of OTEC-ECTF with emphasis on total system.

OTEC-ECTF

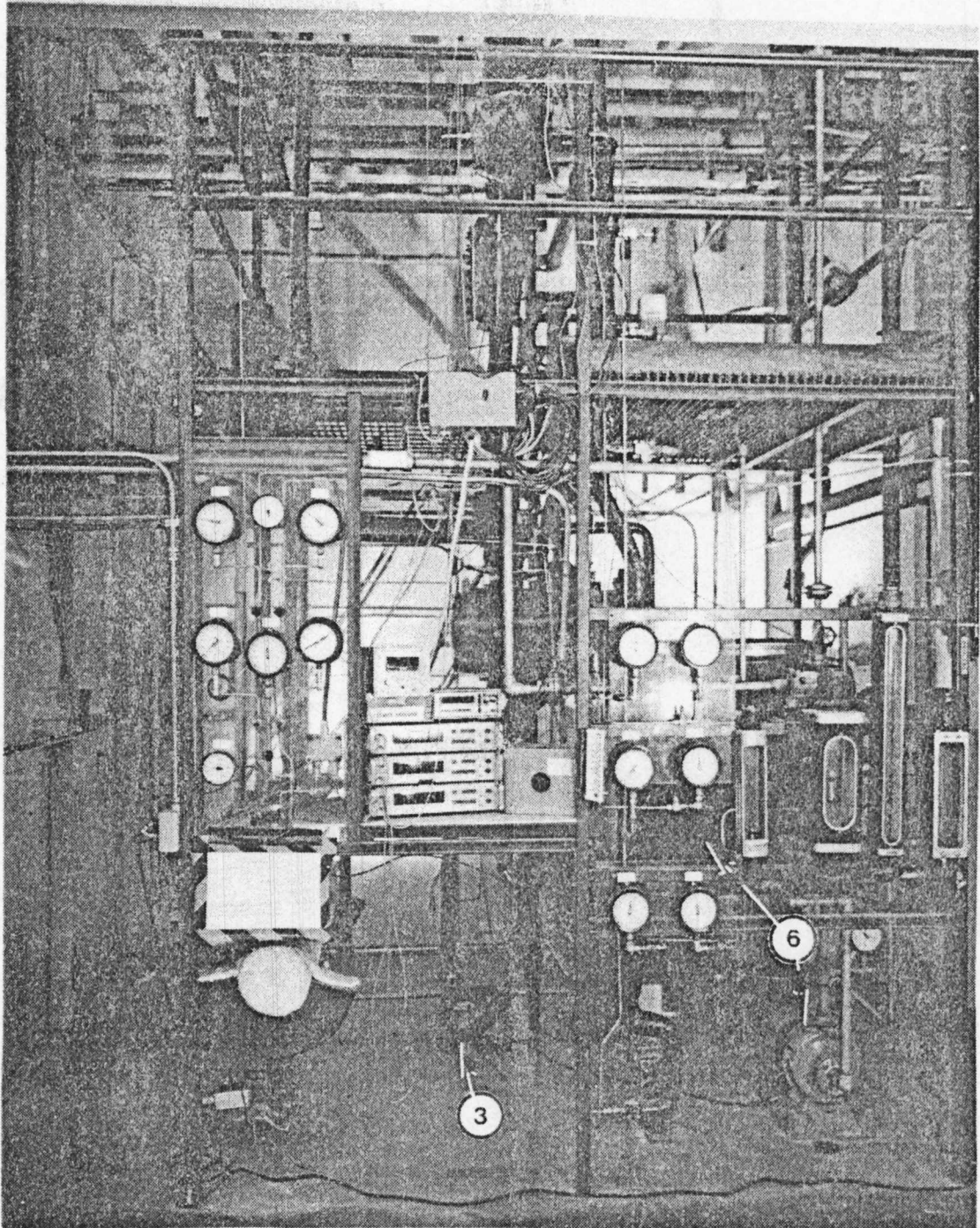


Fig. 3.3. Overall view of OTEC-ECTF with emphasis on instrumentation.

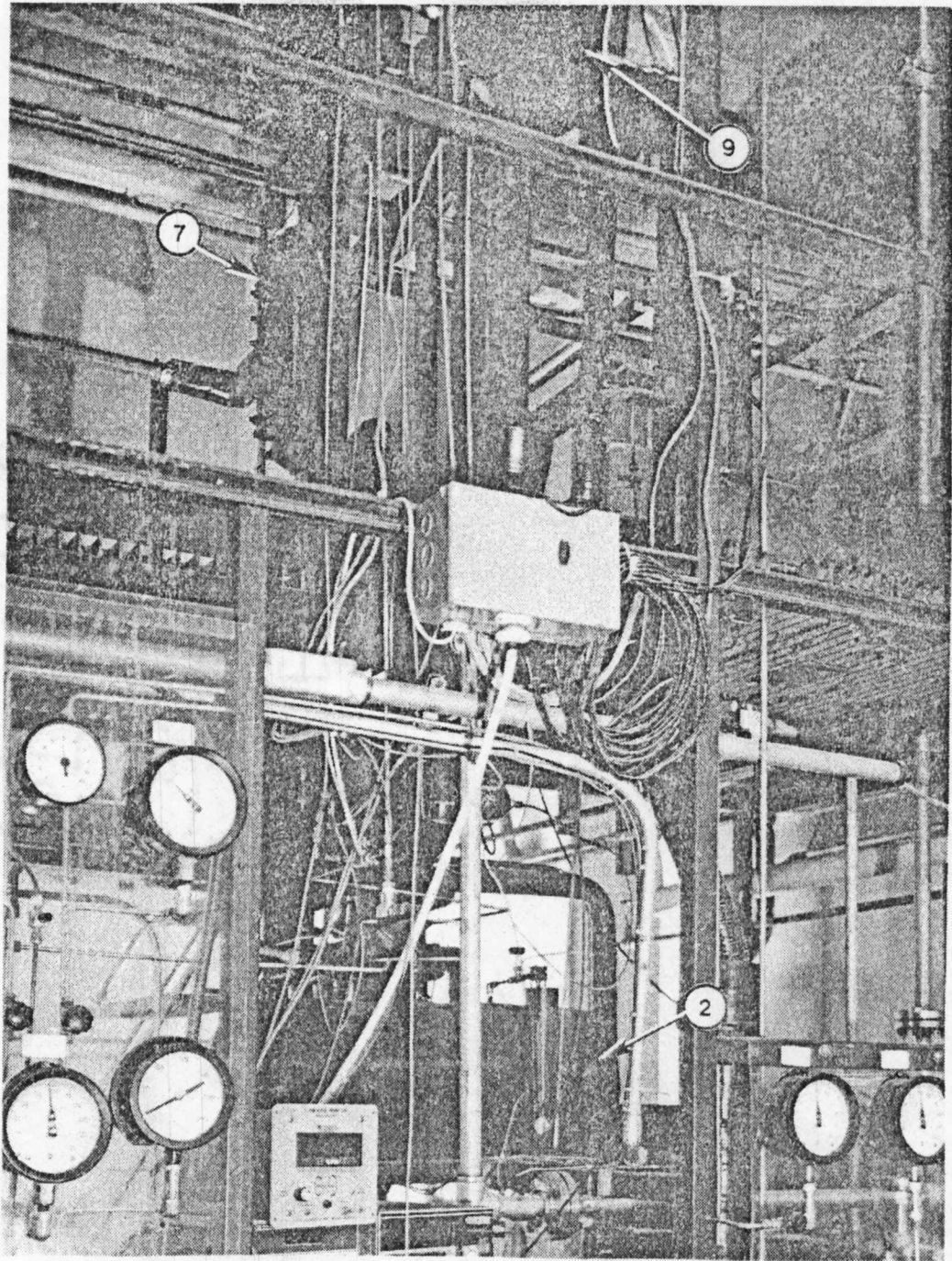


Fig. 3.4. Overall view of OTEC-ECTF with emphasis on evaporator module and ammonia reservoir.

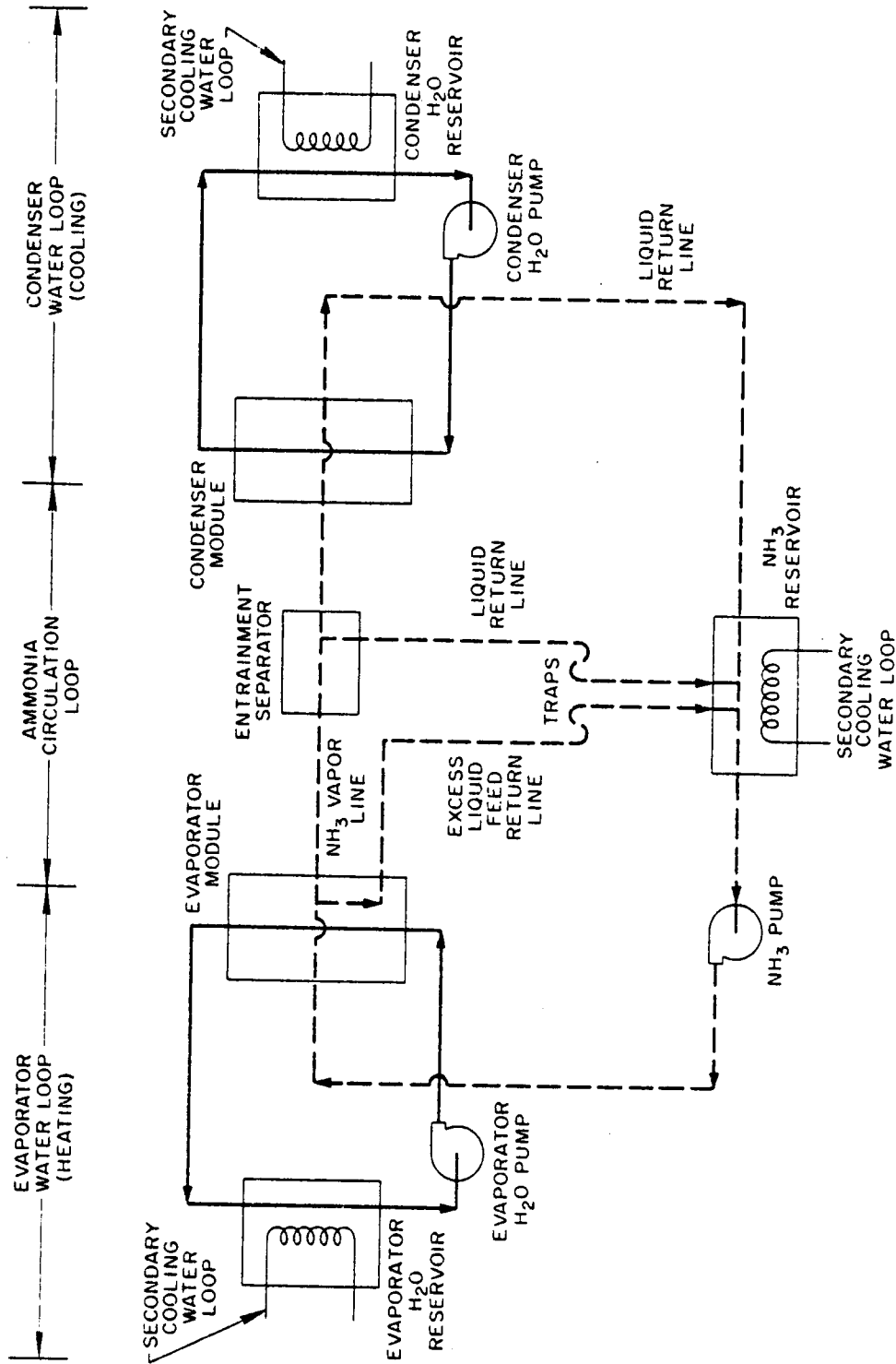


Fig. 3.5. Simplified schematic flow diagram of OTEC-ECTF.

reservoir, through a filtering device, to the top of the evaporator module and distributed as a freely falling thin film on the outside of the evaporator tube. Ammonia flow to the evaporator module was controlled by a regulating valve, and measured by an orifice flowmeter located upstream of the test section. Excess ammonia liquid feed, along with ammonia vapor formed during the evaporation process, exited at the evaporator bottom and collected in the separator cup. A manually operated valve located at the bottom of the separator cup was used to maintain a constant liquid level. Excess ammonia liquid was drained through the valve to the ammonia reservoir. Ammonia vapor from the side of the cup passed through an entrainment separator and entered at the condenser module top. Vapor condensed on the tube outside in the condenser module, exited as a saturated liquid at the condenser bottom, and passed through a condensate measuring station before returning to the ammonia reservoir.

In the primary evaporator heating loop, warm demineralized water was circulated by a centrifugal pump from the evaporator storage tank upward through the evaporator module and back to the storage tank. A pneumatically controlled bypass valve and a manually operated valve, in conjunction with a vortex shedding flowmeter located upstream of the evaporator, were used for flow rate control and measurement.

Another centrifugal pump transferred cool, demineralized water in the primary condenser cooling loop from the condenser storage tank upward through the inside of the condenser module tube and back to the storage tank. The primary cooling water flow rate was measured by rotameters located upstream and controlled by a hand valve located downstream of the condenser module.

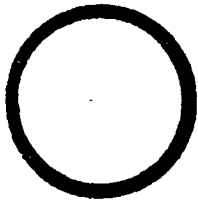
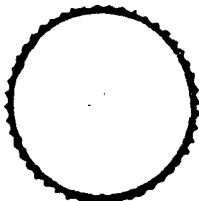
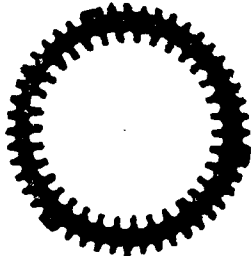
Removing heat from each of the primary loops, plant process water circulated through cooling coils located in the evaporator storage tank, the ammonia reservoir, and the condenser storage tank. In each case, secondary coolant flow rates were regulated by manually operated valves and measured by rotameters located upstream of the cooling coils. Plant process water-line pressure furnished adequate circulation through each secondary coolant loop.

3.2 Experiment Tubes

The performance of three tubes 25.4 mm (1 in.) nominal diameter was examined in this investigation. Detailed descriptions and letter designations of the tubes are presented in tabulated form (Table 3.1) and photographically (Fig. 3.6). All tubes were aluminum: tube A had a smooth inside and outside surface; tube F had a smooth inside surface and 48 external flutes (corrugations); and tube H had 34 internal and 42 external flutes.

Tube A is a standard smooth tube, while tube F is distributed by the Macklanburg Duncan Company as a shower curtain rod sold in hardware stores. Tube H is an experimental tube designed, tested, and supplied by Carnegie-Mellon University. The total outside surface areas of the fluted tubes (Table 3.1) were calculated by two methods: measurement of perimeters, and measurement of enlarged photographic cross sections of tube samples. The active length of smooth tube A was 1.22 m (48 in.), while the effective length for the fluted tubes was 1.17 m (46 in.). Approximately 25.4 mm (1 in.) at each end of the fluted tubes was taken up by sleeve and installation clearances.

Table 3.1. Tube characteristics

Cross section	Tube designation	Inside diameter [cm (in.)]	Outside perimeter [cm (in.)]	Outside surface area [m ² (ft ²)]	Number of outside flutes
	A	2.21 (0.87)	7.98 (3.14)	0.0974 (1.05)	
	F	2.29 (0.90)	8.26 (3.25)	0.0964 (1.04)	48
	H		14.00 (5.51)	0.163 (1.76)	42 ^a

^aAlso contains 34 inside flutes.

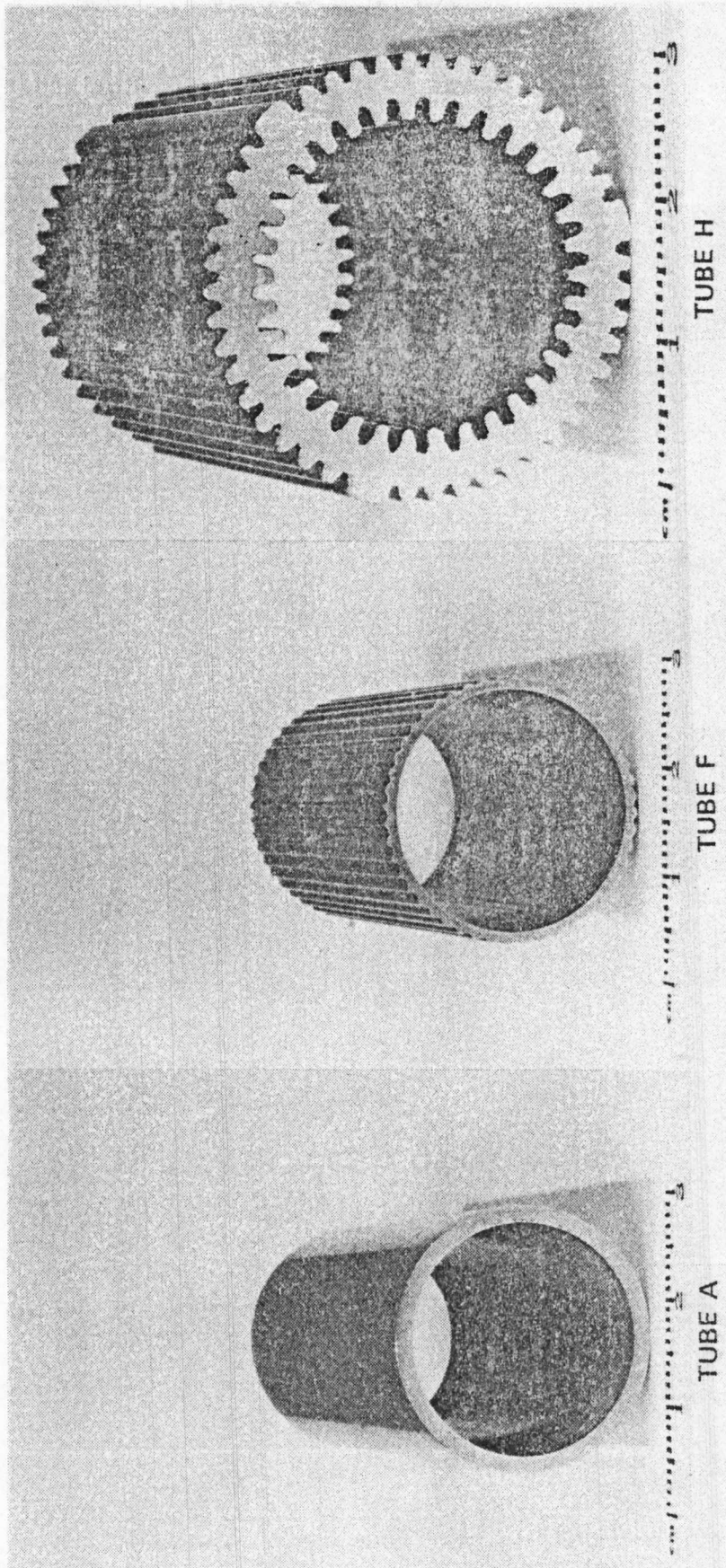


Fig. 3.6. Photographs of tube samples — tubes A, F, and H.

3.3 Ammonia Reservoir

The ammonia reservoir (Fig. 3.7) was fabricated by rolling a 9.53-mm (3/8-in.) stainless steel plate to 254 mm (10 in.) ID. Schedule 80 stainless steel pipe caps were welded to each end, thus forming a closed vessel. This reservoir served as a storage volume for 0.0303 m^3 (8 gal) of liquid ammonia, while also providing the necessary head for the ammonia pump. A sight glass was connected to the side of the reservoir for monitoring the liquid ammonia level. To remove heat from the stored ammonia, process water (secondary coolant) was circulated through a coil of stainless steel tubing 2.85 m (112 in.) long $\times$ 9.53 mm (3/8 in.) OD located inside the reservoir. Swagelok fittings were welded to the reservoir body at several locations to provide inlet and outlet ports to the vessel and to accommodate pressure and temperature monitoring devices.

3.4 Ammonia Pump

Liquid ammonia was transferred from the ammonia reservoir to the top of the evaporator module by a seal-less, centrifugal, canned rotor pump (Crane Chempump, Model GA-1K-7518-3T). This pump was rated at $1.89 \times 10^{-4} \text{ m}^3/\text{s}$ (3.0 gpm) at 11.7 m (38.5 ft) of head, and was driven by a 0.75-kW (1.0-hp) motor. All pump parts in contact with the pumped fluid (ammonia) were of stainless steel material, thus minimizing compatibility problems.

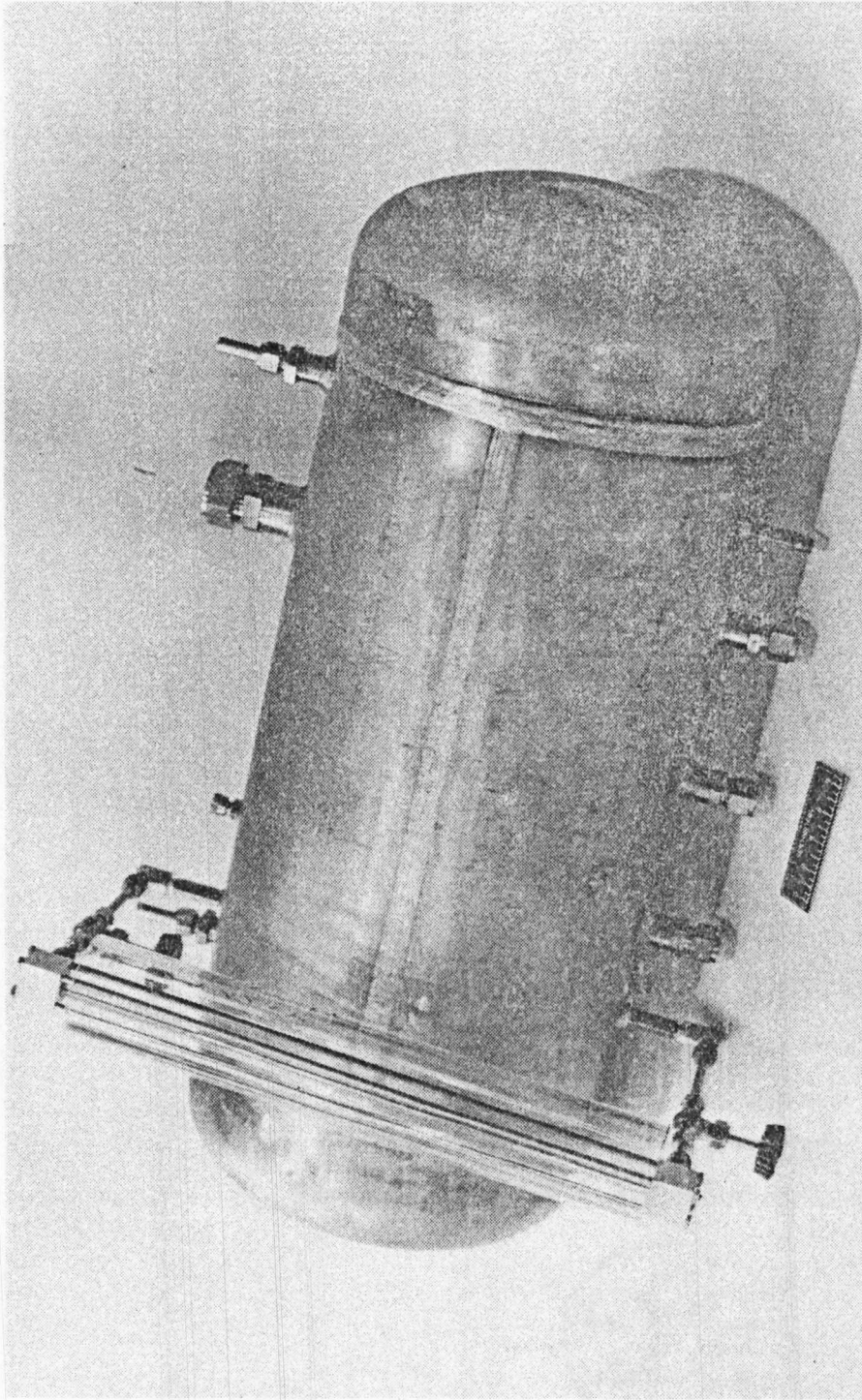


Fig. 3.7. Ammonia reservoir.

3.5 Entrainment Separator

The entrainment separator was constructed from a 304.8-mm (1.0-ft) length of 152.4-mm (6.0-in.) schedule-40 stainless steel pipe. Two stainless steel mesh demistors (Otto H. York Company, 6 in. diam by 6 in. thick), located in the separator body, removed entrained liquid from the ammonia vapor. The separator was mounted at a 30° angle to the horizontal in the vapor line, connecting the evaporator to the condenser. Thus, vapor exits at the highest point; liquid exits at the lowest point and returns through a liquid trap to the ammonia reservoir.

3.6 Evaporator Water Storage Tank and Pump

The evaporator water storage tank (Fig. 3.8) was fabricated from a 6.35-mm-thick (1/4-in.) $\times$ 914.4-mm-wide (36-in.) plate rolled into a drum 1.22 m (48 in.) in diameter. This tank served as a storage volume for the 1.1356 m³ (300 gal) of primary evaporator heating water (demineralized water), and also provided the liquid head necessary for the centrifugal water pump. Located within the tank, a coil of copper tubing 15.24 m (50 ft) long $\times$ 12.7 mm (1/2 in.) OD provided for heat removal from the primary evaporator heating water to the secondary cooling water (process water) circulating through the coil. A Plexiglas cover was mounted on top of the tank to minimize primary water contamination and splash-over.

A centrifugal pump (Allis Chalmers, type CB), rated at 9.46×10^{-3} m³/s (150 gpm) at 48.8-m (160-ft) head and driven by an 11.9-kW (15-hp) motor, transferred demineralized water from the storage tank upward through the evaporator module. A manually controlled gate valve, in

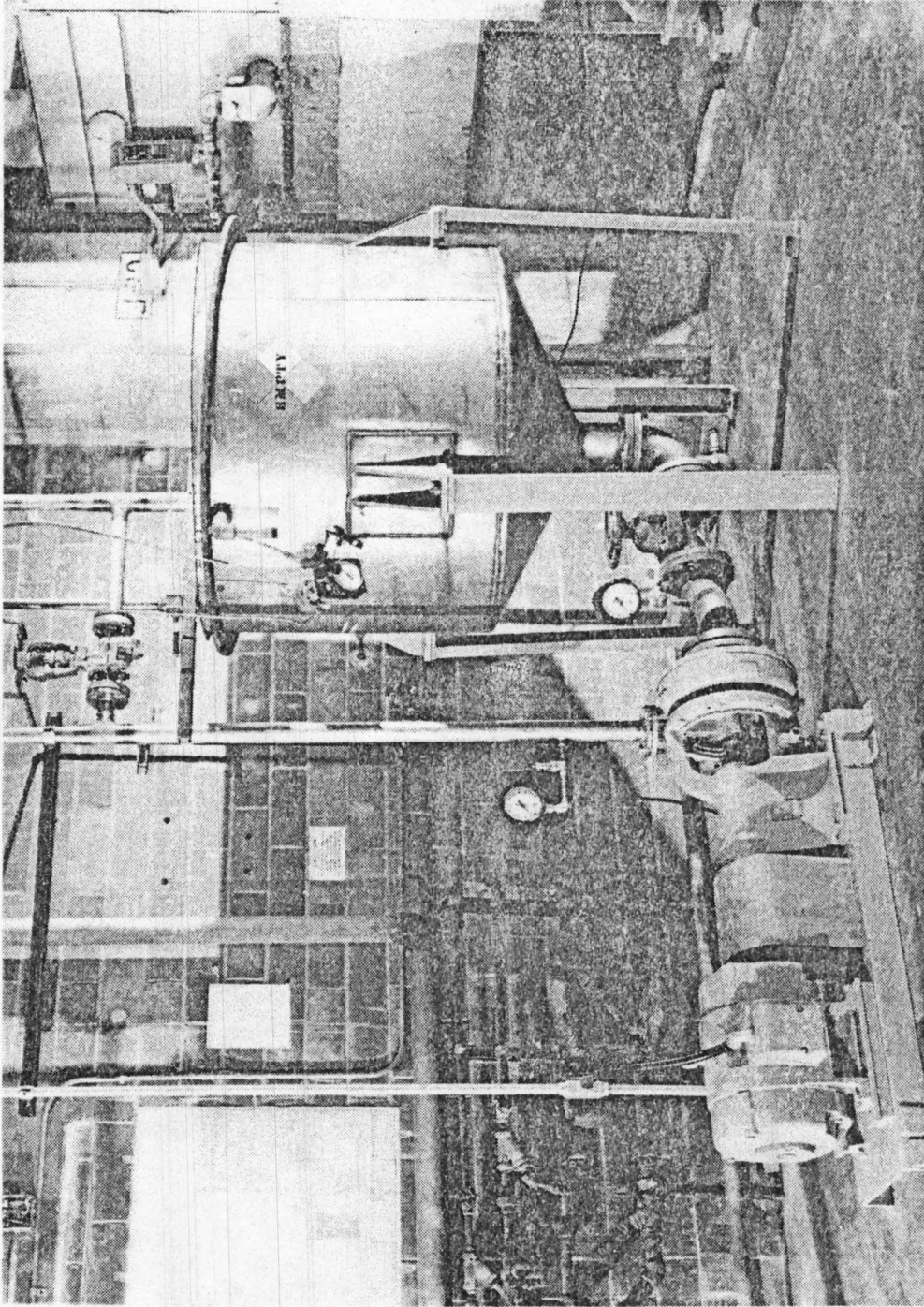


Fig. 3.8. Primary evaporator water storage tank and pump.

conjunction with a pneumatic control bypass valve (Domtor, Model 1 1/2-800) and bypass line located upstream of the evaporator, was used to obtain the desired water flow rates through the evaporator module.

3.7 Condenser Water Storage Tank and Pump

The condenser water storage tank was fabricated from a 55-gal stainless steel drum. While serving as a storage volume for the condenser primary cooling water, this tank also provided the necessary liquid head for the condenser water circulating pump. Located within the drum, a coil of copper tubing 30.5 m (100 ft) long $\times$ 12.7 mm (1/2 in.) OD provided for heat removal to the secondary plant process cooling water circulated through this loop. The condenser primary cooling water was circulated by a centrifugal pump (Gould Pumps, Model 3196 ST), rated at $1.89 \times 10^{-3} \text{ m}^3/\text{s}$ (30 gpm) at 51.8-m (170-ft) head and driven by a 5.6-kW (7.5-hp) motor. Plant process water-line pressure furnished adequate circulation through the secondary cooling coils.

3.8 Evaporator Module

3.8.1 Shell and heads

The evaporator module is presented in a detailed sketch (Fig. 3.9) and in an overall view (Fig. 3.10). The evaporator module shell was fabricated from a 1.06-m (41 5/8-in.) section of 2-in. schedule-40 stainless steel pipe with 2-in., 150-lb stainless steel flanges welded to each end. The outside of the evaporator test tube could be viewed through a stainless steel weld pad gage (Strahman Valves, Model SVT-4W) located midway between the end flanges on the evaporator shell. Two identical heads, fabricated from stainless steel bar stock, were bolted

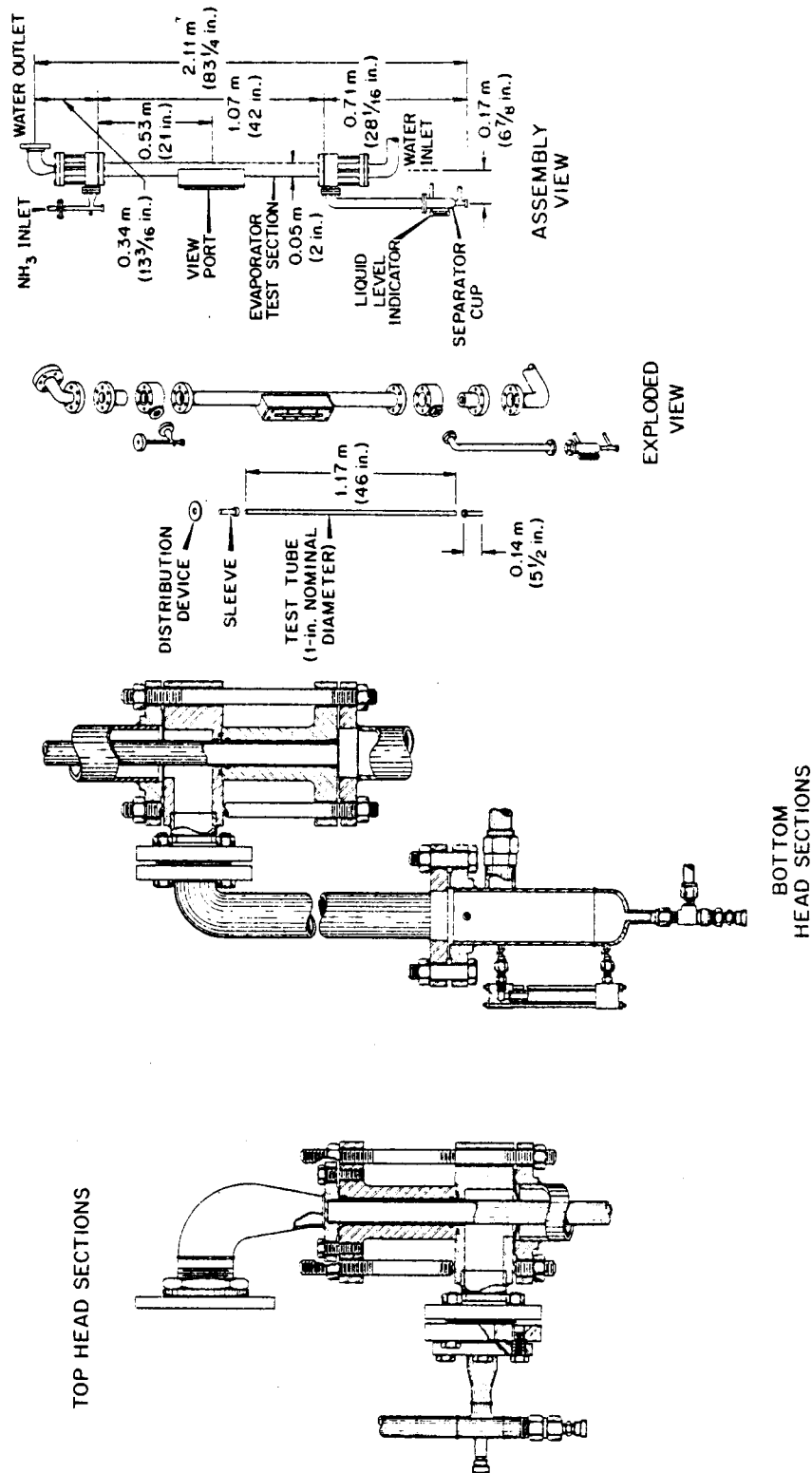


Fig. 3.9. Detailed sketch of evaporator module and head sections.

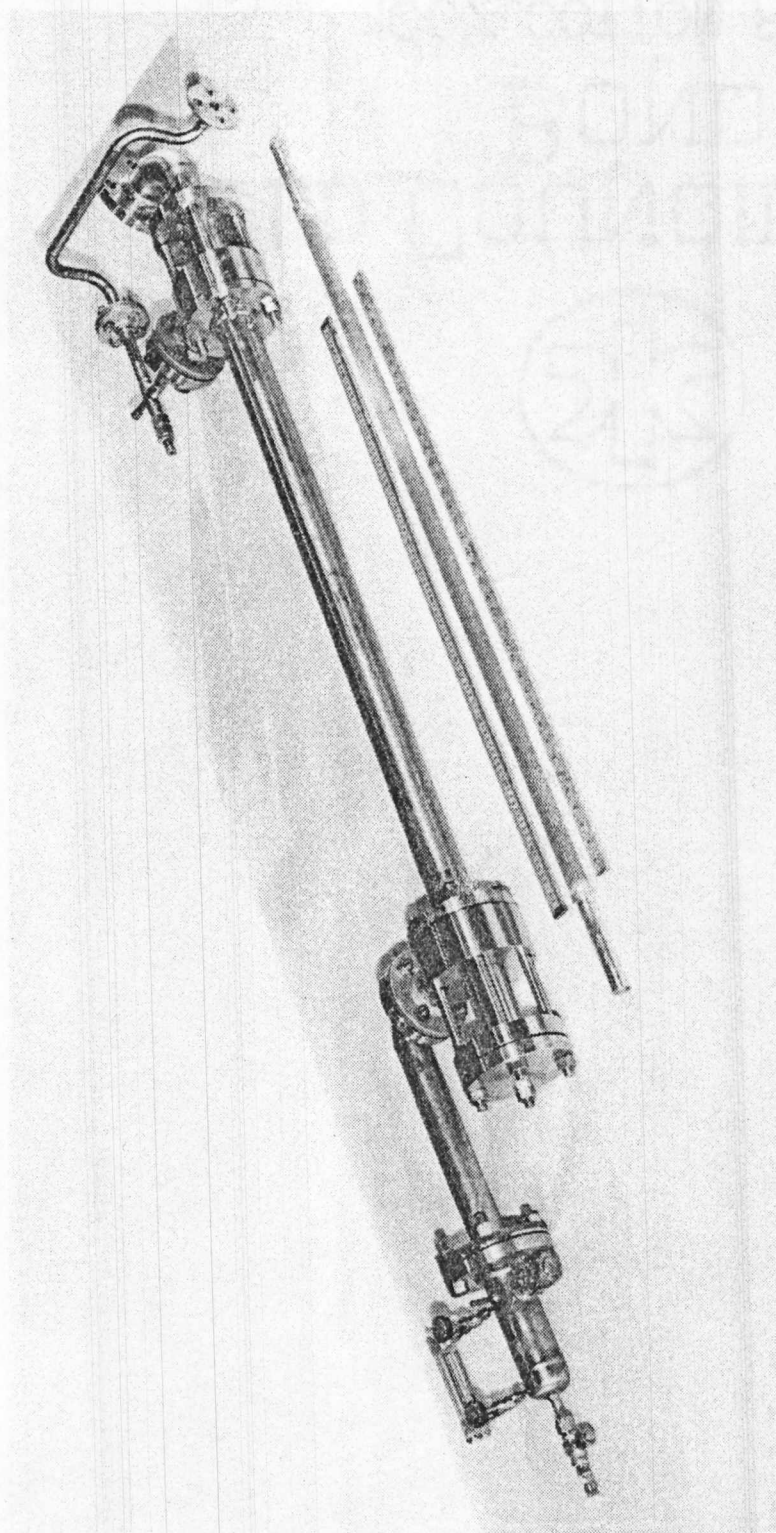


Fig. 3.10. Overall view of assembled evaporator module.

to the flanges at each end of the shell. Each head consisted of two sections -- a side port (ammonia) section and an end port (water) section. The side port section was bolted directly to the shell flange. A 44.8-mm-diam (1.76-in.) O-ring seal was used on the opposite face of the side port section to adapt and seal the end port head section. The end port section contained two 25.4-mm-diam (1-in.) O-ring seals for sealing a 25.4-mm-OD (1-in.) test tube. These head sections provided inlet and outlet passages for ammonia and primary evaporator (heating) water to the evaporator module.

3.8.2 Ammonia distribution device

Liquid ammonia was applied as a freely falling thin film on the outside of the evaporator tube by a distribution device (Fig. 3.11) consisting of a 1.6-mm-thick (1/16-in.) $\times$ 88.9-mm-OD (3.5-in.) neoprene gasket, which was clamped between the shell flange and the side port head section located at the evaporator module top. A hole was cut in the gasket middle, 3.2 mm (1/8 in.) larger than the test tube OD, thus providing a small, uniform gap for liquid flow between the gasket edge and the outside tube wall. As the ammonia feed rate was increased, this diaphragm-like distribution device deflected downward, enlarging the gap between the gasket edge and the tube wall. As the ammonia feed rate was decreased, the distribution device resumed its original configuration.

3.8.3 Separator cup

The separator cup (Fig. 3.12), located at the bottom of the evaporator module, was fabricated from a 152.4-mm (6-in.) length of 2-in. schedule-40 stainless steel pipe with a 2-in. stainless steel pipe cap welded to the lower end, and a 150-lb slip-on flange welded to the other end.

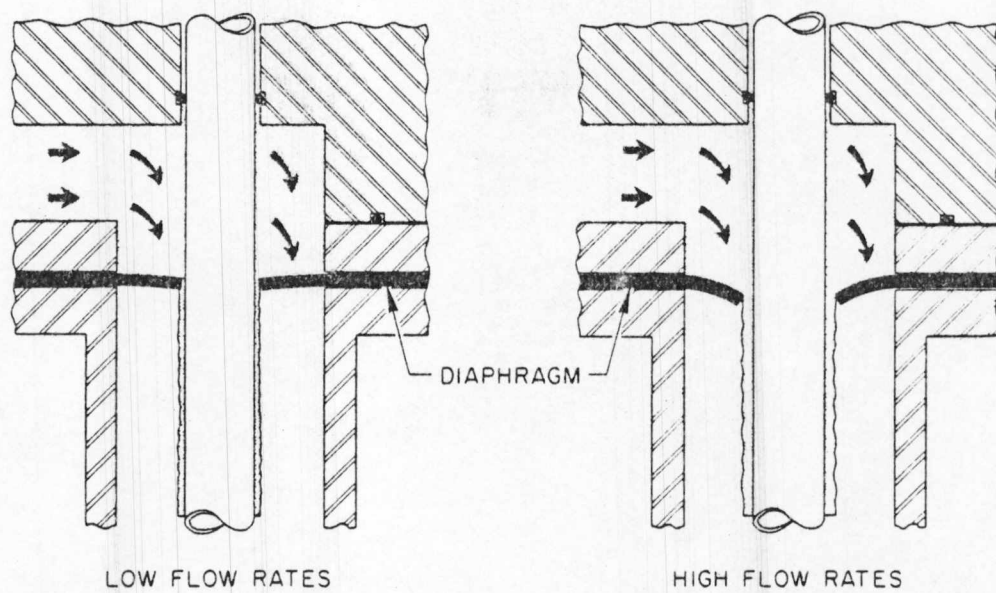


Fig. 3.11. Detail view and principle of operation of ammonia distribution device.

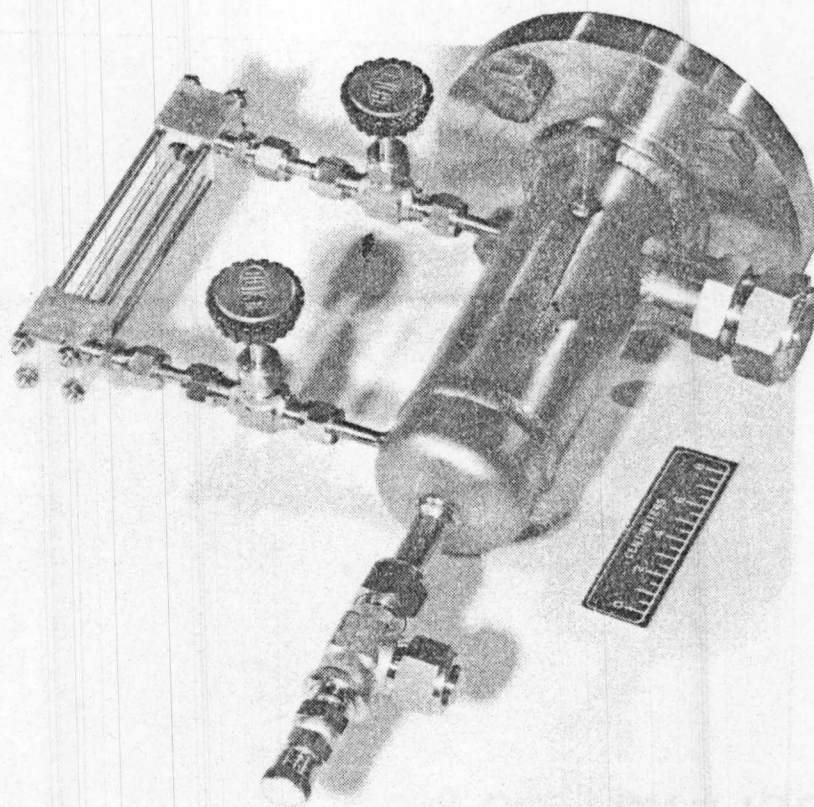


Fig. 3.12. Ammonia separator cup.

A sight glass was mounted on the side of the cup for monitoring the liquid level inside. Ports located at the side and bottom of the cup allowed measurement of temperature and pressure of the contents. A manually operated valve was used to maintain a constant liquid level in the separator cup, while draining excess liquid from the cup bottom back to the ammonia reservoir. Ammonia vapor exited at the separator cup side, enroute to the top of the condenser module.

3.8.4 Evaporator tube installation

The heads on the evaporator module were designed to seal around a smooth 25.4-mm-OD (1-in.) tube. Experimental test tubes, other than smooth tube A, were prepared by aluminum welding a 25.4-mm-OD (1-in.) sleeve 133.35 mm (5 1/4 in.) long to each end of a 1.17-m (46-in.) length of tube. One end of a prepared test tube is shown in Fig. 3.13 to illustrate this sleeve connection. For installation, (1) the two top head sections were removed; (2) the test tube was inserted downward into the evaporator module shell until the bottom sleeve slid through the two O-ring seals in the lower bottom head section; (3) the ammonia distribution device was then slipped around the test tube top and centered, while mounting the side port head section to the top of the evaporator module; and (4) the end port head section was then slipped over the top sleeve and bolted through the side port section to the top shell flange to complete the shell-side sealing operation. Next, required connections were made to the primary water heating loop and the ammonia circulation loop.

For tests with tube F, a 12.7-mm-OD (1/2-in.) stainless steel rod was installed through the center of the evaporator module (inside the

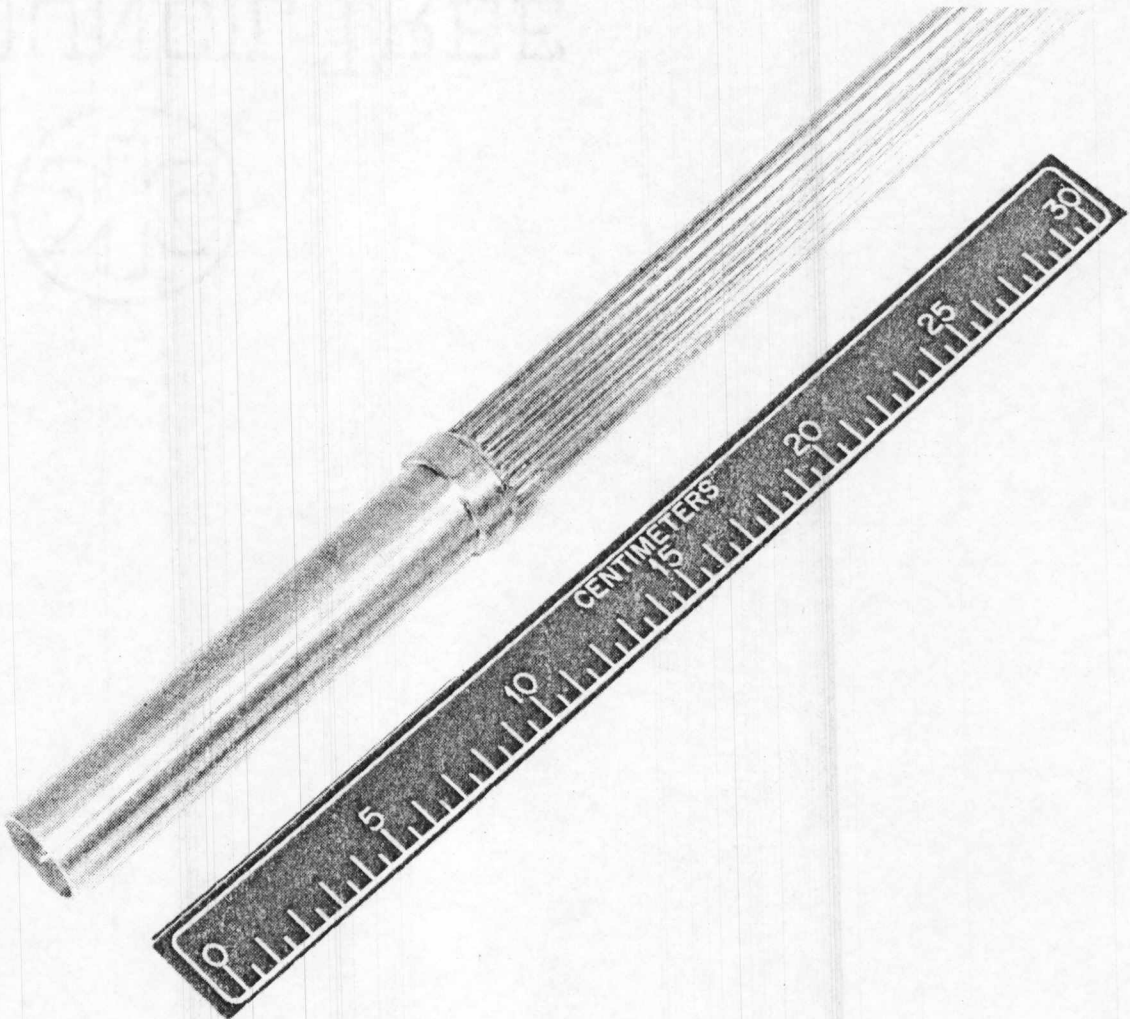


Fig. 3.13. Sleeve connection for sample test tube.

test tube) in order to decrease the hydraulic diameter and increase the water velocity for a given primary water volume flow. Both variations tended to increase the water-side heat transfer coefficients and, as a result, improved the accuracy of the Wilson-plot technique used to interpret the experimental data.

3.9 Condenser Module

3.9.1 Shell and heads

A detailed sketch of the condenser module is presented in Fig. 3.14. The condenser module shell was fabricated from a 1.09-m (42.87-in.) section of 4-in. schedule-40 stainless steel pipe with 150-lb stainless steel flanges welded to each end. The outside (condensing) surface of the condenser tube could be viewed through two windows located near the top and bottom. Two heads, fabricated from stainless steel bar stock, were bolted to each end of the shell. The top head consisted of two sections — upper and lower — designed to facilitate tube installation and removal. The lower section, bolted directly to the top flange, contained a radial 25.4-mm-diam (1-in.) hole for the vapor entrance. The upper section, containing four 25.4-mm-diam (1-in.) O-ring seals for sealing a 25.4-mm-OD (1-in.) tube, was bolted to the lower section of the top head. The bottom head consisted of only one section, containing four 25.4-mm-diam (1-in.) O-ring seals and a radial 25.4-mm-diam (1-in.) hole, for exit of condensate from the condenser module.

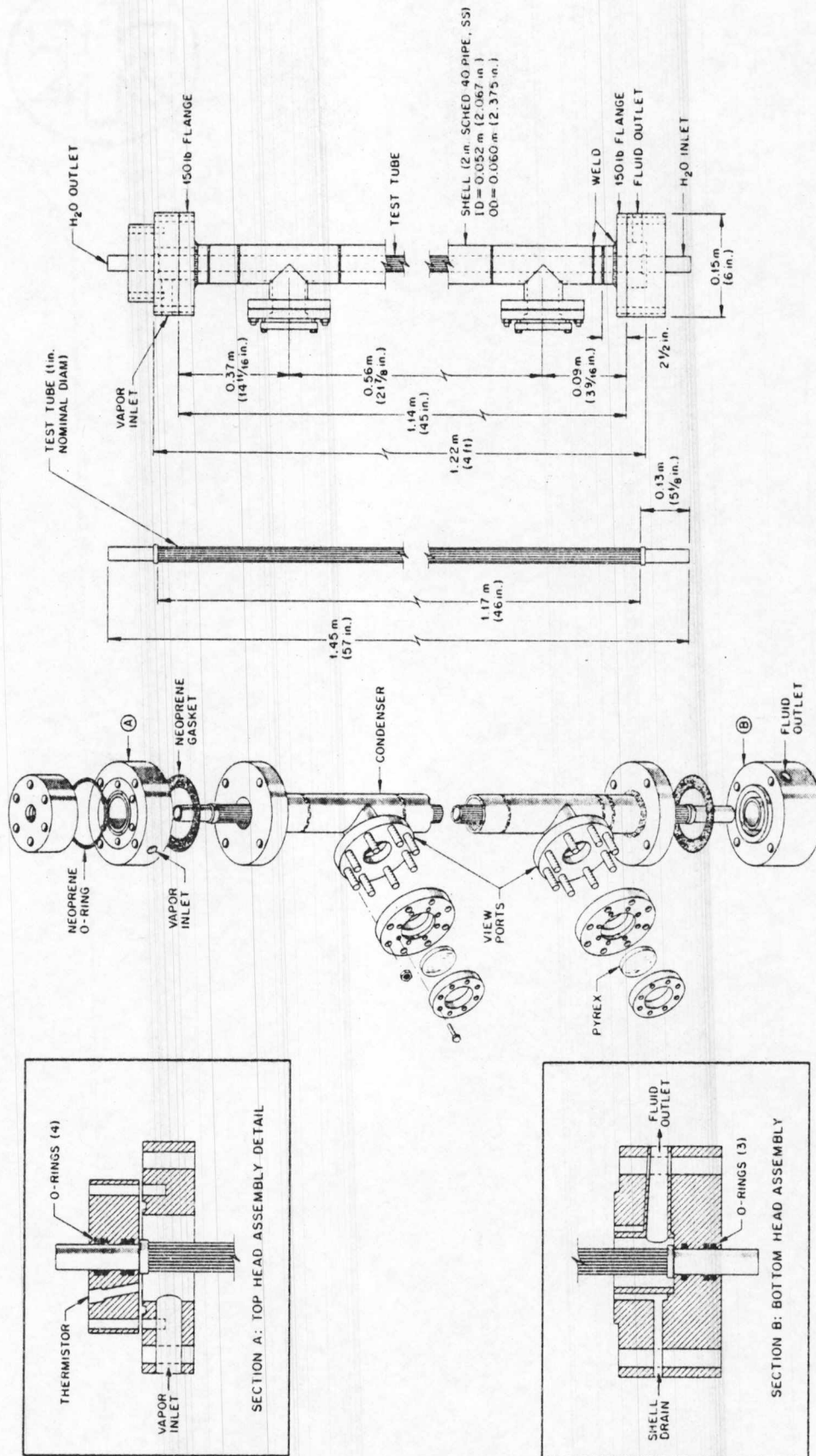


Fig. 3.14. Details of condenser module.

3.9.2 Condenser tube and installation

Fluted tube F was used as the condensing surface in the condenser module. Since the heads were designed to seal around a 25.4-mm-OD (1-in.) tube, it was necessary to prepare the condenser tube in the same manner as the evaporator tubes, with a sleeve welded to each end. For installation, (1) the upper section of the top head was removed; (2) the tube was inserted downward into the condenser shell until the bottom tube sleeve slipped through the four O-ring seals in the bottom head; and (3) the upper section of the top head was then slipped over the top sleeve and bolted to the lower section to complete the shell-side sealing operation. Next, required connections were made to the primary cooling loop.

3.10 Vent and Vacuum Systems

A port for venting the system was provided at the top of the condenser test section. Various sections were interconnected by vent lines to provide pressure equilization and allow steady loop operation. A vacuum pump, connected to the loop at several locations, permitted evacuation of isolated sections for maintenance purposes.

3.11 Seals and Gaskets

The ammonia loop was normally equipped with neoprene gaskets and seals, although teflon was used for several applications. Minimal compatibility problems were encountered between the ammonia and the seals and gaskets during experimental operation.

4. PROCEDURES AND INSTRUMENTATION

This experimental study was undertaken to determine heat transfer coefficients for thin film evaporation of ammonia on the outside surface of single vertical tubes. Water, circulating at relatively high velocities inside the tubes, served as the heat source. Two methods were used for eliminating water-side coefficients from overall coefficients, thus isolating evaporation heat transfer coefficients: the Wilson-plot technique, and standard correlations for determining water-side coefficients. The necessary heat rates and temperature differences were calculated from experimental data taken during steady-state operations (Appendix A has sample calculations). Accurate temperature measurements were critical, since it was sometimes necessary to measure temperature differences as small as 0.07°F . Further, flow rates as small as 0.05 gpm had to be measured accurately for good interpretation of experimental data. Operating procedures and instrumentation are described in detail in the following sections.

4.1 Operating Procedures

4.1.1 Filling

Before filling operations began, the ammonia loop was evacuated (~ 28 in. Hg) by the vacuum pump. Once evacuation was complete, ammonia vapor was introduced at the top of the condenser module. Primary cooling water, circulating through the condenser tube, caused the ammonia to condense and flow as a liquid to the ammonia reservoir. The liquid level in the reservoir was monitored visually by the liquid level

indicator. When three-fourths filled with liquid, the reservoir was closed off from the vessel supplying the ammonia, and the system was ready to operate.

4.1.2 Experimental loop start-up

A standard start-up procedure was implemented for each day of experimental tests. Primary cooling water was first circulated through the condenser module at the maximum flow rate of $2.1450 \times 10^{-3} \text{ m}^3/\text{s}$ (34 gpm). The secondary condenser cooling water loop was then adjusted to the desired flow rate, 0 to $5.3627 \times 10^{-4} \text{ m}^3/\text{s}$ (0 to 4 gpm), to control the temperature of the primary condenser cooling water. After the primary evaporator heating water was circulated at the maximum flow rate through the evaporator module, the secondary evaporator cooling water loop was adjusted to the desired flow rate, 0 to $6.0733 \times 10^{-4} \text{ m}^3/\text{s}$ (0 to 5 gpm), thus removing heat and controlling the temperature of the primary evaporator heating water. Liquid ammonia was pumped at the desired feed rate to the top of the evaporator module and distributed as a freely falling film on the evaporator tube outside surface. The secondary ammonia cooling loop was then adjusted to the desired flow rate, 0 to $6.0733 \times 10^{-4} \text{ m}^3/\text{s}$ (0 to 5 gpm). In conjunction with the condenser module cooling loops, the secondary ammonia cooling loop removed heat (added by the ammonia pump and the evaporator module) from the ammonia.

4.1.3 Steady-state operation

After start-up, a constant liquid level was maintained in the separator cup, and temperatures and pressures throughout the system were

monitored to determine when steady-state conditions existed. Steady state was assumed when there was no significant change in temperatures ($\pm 0.2^\circ\text{F}$) and primary flow rates ($\pm 2\%$) throughout the system over a 10-min. span. Once steady-state was achieved, the following experimental data were recorded: flow rates and inlet and outlet temperatures for each primary loop, flow rates for each secondary loop, and pressures at various points in the ammonia circulation loop. These experimental data were then used to calculate heat transfer rates, temperature differences in the system, and to check pressure-temperature values against saturation data in the literature.¹⁵

After the data were recorded for a given steady-state condition, the flow rates of the evaporator primary heating and secondary cooling water were adjusted until a new steady-state condition was reached. Experimental data were again recorded and the procedure was repeated. The same procedure was followed until data were collected for six or seven primary heating water flow rates, at approximately the same evaporation heat rate, usually completing a day of testing. The following day, the entire start-up procedure was repeated and experimental tests were made at a new heat rate, established by adjusting the flow rates of the evaporator secondary cooling water. The same procedures were followed daily, until the data sufficiently spanned the heat load ranges of interest.

4.2 Experiment Test Plan

The test plan followed for evaporation tests with each experimental tube is shown in Fig. 4.1. Typically, the highest ammonia feed rate,

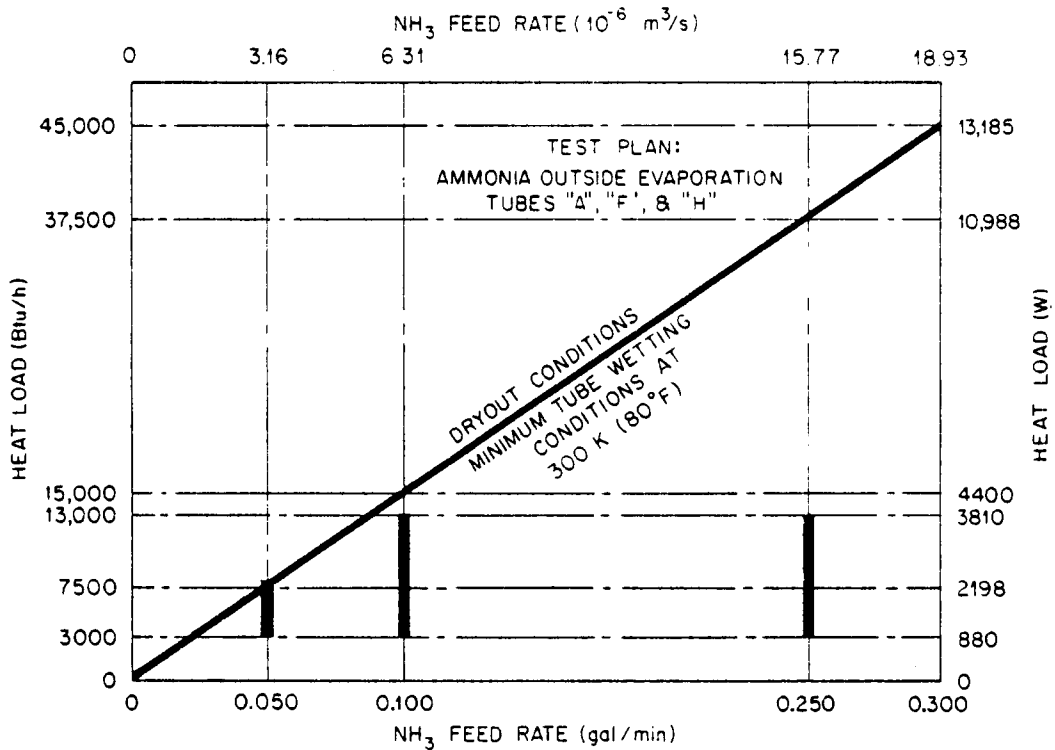


Fig. 4.1. Test plan followed for evaporation tests on tubes A, F, and H.

$1.5773 \times 10^{-5} \text{ m}^3/\text{s}$ (0.25 gpm), was tested first with a given tube. Each day the heat load was gradually increased, from 880 W (3000 Btu/h) up to 3810 W (13,000 Btu/h). Upon completion of tests spanning the heat load range, the ammonia feed rate was decreased to $6.3092 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm) and the heat load range was repeated. This procedure was again repeated for an ammonia feed rate of $3.1546 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm) up to a heat load of ~7000 Btu/h, or until tube surface dryout conditions occurred. Dryout conditions were judged visually through the view port located on the evaporator shell. The same procedure was used for each of the three experimental tubes tested.

4.2.1 Pressure

The pressures in the evaporator module, the condenser module, and the ammonia reservoir were measured with gages (U.S. gage) capable of spanning the range 0 to 2.0864×10^3 kPa (0 to 300 psi). The ammonia circulation loop was also equipped with a compound gage for reading low and subatmospheric pressures.

4.2.2 Temperature

The experimental loop was equipped at various locations with Chromel-Alumel thermocouples, which were read with a potentiometer, to obtain temperatures used for monitoring loop operation. Two multipoint recorders were available to obtain a permanent record of temperature measurements.

Thermistors (Thermometrics, part No. S-10-4-wire) and quartz thermometers (Hewlett-Packard, model 2801A) were installed in the water inlet and outlet lines of both the condenser and evaporator modules and in the ammonia vapor feed line to the condenser. In addition, thermistors were located in the liquid ammonia feed line at the top and in the separator cup at the bottom of the evaporator module. A digital multimeter (Data Precision, model 3500) was used for determining thermistor temperature measurements. The information from the thermistors was used for data reduction, because of the greater accuracy attributed to these instruments. The three sets of temperature measuring instruments were checked against each other to increase confidence in the temperature measurements.

4.2.3 Flow rate

The ammonia feed rate to the evaporator module was measured by an integral flow orifice assembly, adapted to a pneumatic d/p cell transmitter (Foxboro model 15A). With the integral orifice meter, it was necessary to change orifice plates (bores of 0.0595, 0.0810, and 0.0995 in.) for the various feed rate ranges. Located upstream of the evaporator module, a vortex shedding flowmeter (Eastech model VS-21) was used to measure primary heating water flow rates in the range of 6.309×10^{-4} to $6.309 \times 10^{-3} \text{ m}^3/\text{s}$ (10 to 100 gpm).

The primary cooling water flow was measured by a rotameter located upstream of the condenser module. Rotameters that ranged from 0 to $2.5236 \times 10^{-4} \text{ m}^3/\text{s}$ (0 to 4 gpm) were used for monitoring secondary coolant flows through the cooling coils located in the evaporator water storage tank, the condenser water storage tank, and the ammonia reservoir.

5. ANALYSIS

5.1 Overall Evaporation Coefficients

The overall coefficient in the evaporator can be written

$$U_o = \frac{Q}{A_{t,o} \overline{\Delta T}}, \quad (5.1)$$

where $\overline{\Delta T}$ is the mean temperature difference between the evaporating ammonia liquid and the primary (heating) water, $A_{t,o}$ is the total outside heat transfer surface area of the tube, and Q is the evaporator heat rate. The arithmetic mean water temperature was used in calculating $\overline{\Delta T}$, since the difference between the inlet $T_{w,in}$ and outlet $T_{w,out}$ was relatively small [less than 1.7 K (3.0°F)] in most cases. Therefore, assuming saturated ammonia liquid at the bottom of the separator cup

$$\overline{\Delta T} = \left[\frac{(T_{w,in} + T_{w,out})}{2} \right] - T_{N,o}, \quad (5.2)$$

where the first term on the right is the average of the inlet $T_{w,in}$ and outlet $T_{w,out}$ water temperatures, and $T_{N,o}$ is the ammonia outlet temperature in the cup. During steady-state operation, the ammonia inlet temperature was, at most, 1.1 K (2.0°F) subcooled. Since the sensible heat of the ammonia liquid is relatively low (compared to the latent heat of vaporization) over the temperature range tested, the ammonia liquid rapidly reaches the saturation temperature during experimental tests. Thus,

the selection of the ammonia outlet temperature for use in Eq. (5.2) was deemed appropriate.

There are three independent ways of determining the heat rate Q of the evaporator module: (1) from the flow rate and temperature change of the water passing through the evaporator, (2) from an energy balance on the ammonia (refrigerant) side, and (3) from an overall energy balance on the evaporator primary and secondary water circulation loops. Since the experimental loop was designed for measuring the flow rate and temperature change of the water passing through the evaporator, the first method was used exclusively in all calculations for determining the heat rate. The evaporator heat rate may be computed from

$$Q = \dot{m}_w c_{p,w} \Delta T_w , \quad (5.3)$$

where $\dot{m}_w$ is the water mass flow rate, $c_{p,w}$ is the heat capacity of water evaluated at the average water temperature, and ΔT_w is the difference between the inlet $T_{w,in}$ and outlet $T_{w,out}$ water temperatures.

The overall heat transfer coefficient, based on the total tube outside surface area, can be computed from Eq. (5.1), using Eq. (5.2) to calculate $\overline{\Delta T}$, and Eq. (5.3) to calculate Q . The next step in the analysis is the evaluation of individual evaporation-side coefficients from the overall coefficients.

5.2 Individual Heat Transfer Coefficients

The overall resistance to heat flow $ER = 1/U_o$ in an evaporator is equal to the sum of the individual resistances; thus,

$$1/U_o = R_e + R_{wall} + R_w + R_{fo} + R_{fi} , \quad (5.4)$$

where R_e is the resistance of evaporation (ammonia) side, R_{wall} that of the wall, R_w that of the water side, and R_{fo} and R_{fi} account for fouling resistances on the tube outside and inside surfaces. If fouling is neglected and individual heat transfer coefficients h are introduced, the overall coefficient U_o based on the outside surface area becomes

$$1/U_o = 1/h_e + R_{wall} + \frac{A_{t,o}}{A_i h_w}, \quad (5.5)$$

where h_e is the evaporation-side heat transfer coefficient, h_w is the water-side coefficient, and the total inside and outside surface areas of the tube are represented by A_i and $A_{t,o}$.

For a smooth circular tube, the wall resistance based on the outside tube area may be expressed as

$$R_{wall} = \left(\frac{r_o}{k} \right) \ln \left(\frac{r_o}{r_i} \right), \quad (5.6)$$

where k is the thermal conductivity of the metal tube wall, r_o is the outside radius, and r_i is the inside radius of the tube. The wall resistance of fluted tubes is more difficult to determine due to the more complicated surface geometry and heat distribution. In order to compare performance of smooth and fluted tubes tested in this study, it was convenient to combine the evaporation side and wall resistances into a composite heat transfer coefficient h_c^* , defined by

$$1/h_c^* = 1/h_e + R_{wall}. \quad (5.7)$$

Substituting Eq. (5.7) into Eq. (5.5) and rearranging yields

$$h_c^* = \frac{1}{(1/U_o) - (A_{t,o}/A_i h_w)} \quad (5.8)$$

The corresponding composite temperature difference ΔT_c^* is given by

$$\Delta T_c^* = \frac{Q}{h_c^* A_{t,o}}, \quad (5.9)$$

which represents the temperature difference between the inside wall of the tube and the evaporating ammonia. The next step in the analysis is the evaluation of the composite heat transfer coefficient by eliminating the water-side coefficient h_w in Eq. (5.8).

5.3 Elimination of Water-Side Coefficients

5.3.1 Wilson-plot

The primary method used in this study for eliminating water-side coefficients was a technique introduced by Wilson.¹⁶ The Wilson-plot technique is a graphical method of interpreting overall coefficients such that individual evaporation-side coefficients can be evaluated. The following treatment presents the method and describes the application to the experimental data in this study.

Neglecting the effects of changes in water temperature, the water-side resistance for turbulent flow, as a function of the water velocity, may be approximated by

$$1/h_w \propto 1/V^{0.8}; \quad (5.10)$$

and thus, Eq. (5.5) can be rewritten:

$$1/U_o = 1/h_e + R_w + a_1 V^{-0.8} . \quad (5.11)$$

Following Wilson, if the sum of the first two resistances is taken as approximately constant, Eq. (5.11) becomes

$$1/U_o = a_o + a_1 V^{-0.8} . \quad (5.12)$$

In this form, a plot of $1/U_o$ vs $V^{-0.8}$ on ordinary rectangular coordinates should give a straight line from which the constants a_o (y-intercept) and a_1 (slope) can be determined. Since a_o is the sum of the first two resistances in Eq. (5.5), substitution and rearrangement of Eq. (5.7) yields

$$h_c^* = 1/a_o , \quad (5.13)$$

which is the parameter of interest in this analysis.

Experimental data points used in the construction of each Wilson-plot were obtained by maintaining a constant heat load and ammonia feed rate, while varying the water-side velocities. Fluid properties did not vary significantly over the small range of temperatures covered during this series of runs (Sect. 6); thus, no appreciable error was introduced by assuming that the sum of the first two resistances ($1/h_e + R_w$) in Eq. (5.5) was essentially constant.

5.3.2 Alternate method for eliminating water-side coefficients

An alternate scheme was employed as a check of the Wilson-plot results. For fully developed turbulent flow in round tubes, McAdams¹⁷

suggested that water-side coefficients can be estimated by the Dittus-Boelter equation:

$$Nu = 0.023 (Re)^{0.8} (Pr)^{0.4} . \quad (5.14)$$

After substituting parameters for the nondimensional quantities and solving for the water-side coefficient h_w , Eq. (5.14) becomes

$$h_w = 0.023 \left(\frac{k_b}{D} \right) \left(\frac{GD}{\mu} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)_b^{0.4} , \quad (5.15)$$

where the subscript b denotes water properties evaluated at the bulk temperature. Two other widely accepted correlations were also used for estimating water-side heat transfer coefficients for fully developed turbulent flow in round tubes. The first correlation suggested by Colburn¹⁸ is

$$h_w = 0.023 \left(\frac{k_b}{D} \right) \left(\frac{GD}{\mu_b} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)_b^{0.33} \left(\frac{\mu_b}{\mu_{wall}} \right)^{0.14} . \quad (5.16)$$

The second correlation is from the data of Sieder and Tate:

$$h_w = 0.027 \left(\frac{k_b}{D} \right) \left(\frac{GD}{\mu_b} \right)^{0.8} \left(\frac{c_p \mu}{k} \right)_b^{0.33} \left(\frac{\mu_b}{\mu_f} \right)^{0.14} . \quad (5.17)$$

For each experimental run, h_w was calculated from Eqs. (5.15), (5.16), and (5.17), and substituted into Eq. (5.8) to determine the corresponding composite heat transfer coefficient h_c^* . The composite heat transfer coefficient in Eq. (5.8) is very sensitive to the water-side coefficient, especially at low water velocities (low water-side coefficients).

Thus, using the correlation of Eqs. (5.15), (5.16), or (5.17) for determining water-side coefficients is, at best, only approximate (Appendix A). Therefore, this alternate scheme was only used as a check on composite heat transfer coefficients obtained from the Wilson-plot technique.

6. RESULTS AND DISCUSSION

In this investigation, a total of 563 experimental runs, yielding 79 heat transfer data points, were made on thin film evaporation of ammonia on the outside surface of single vertical tubes. Samples of data reduction and the use of Wilson-plots are presented in Appendix A. Smoothed Wilson-plot results and experimental data are documented in Appendix B and C respectively. Experimental results are presented and discussed in the following sections.

6.1 Smooth Tube A

Parameter ranges for the experiments with ammonia evaporating on the outside of smooth Tube A are given in Table 6.1. A total of 190 experimental runs, providing 29 heat transfer data points, were made at three different ammonia feed rates. Tube A data are presented in non-dimensional form in Fig. 6.1. The abscissa is the mean or average liquid film Reynolds number

$$\overline{Re} = 4\overline{\Gamma}/\mu , \quad (6.1)$$

where $\overline{\Gamma}$ is the average mass flow rate per unit length of tube periphery. The ordinate (Fig. 6.1) is the mean or average nondimensional heat transfer coefficient:

$$h_e/\phi = h_e/(k^3\rho^2g/\mu^2)^{1/3} , \quad (6.2)$$

Table 6.1. Parameter ranges for smooth tube A

Parameters	Smooth tube A [Total outside surface area, $A_{t,o} = 0.09727 \text{ m}^2 (1.047 \text{ ft}^2)$]		
	46	78	66
Number of runs	46	78	66
$F_{N,i}$, NH_3 feed rate, $\text{m}^3/\text{s} \times 10^6$ (gal/min)	3.192–3.281 (0.0506–0.0520)	6.322–6.378 (0.1002–0.1011)	15.514–15.703 (0.2458–0.2489)
Q , heat load, W (Btu/h)	800–2,070 (2,740–7,060)	790–3,250 (2,710–11,100)	900–3,500 (3,060–11,950)
$T_{N,o}$, NH_3 temperature, K ($^{\circ}\text{F}$)	300.1–303.9 (80.5–87.4)	295.1–302.9 (71.5–85.5)	292.8–303.0 (67.4–85.7)
F_w , H_2O flow rate, $\text{m}^3/\text{s} \times 10^2$ (gal/min)	5.0–54.1 (8.0–85.7)	5.4–59.7 (8.6–94.6)	5.4–59.6 (8.5–94.5)
V_w , H_2O velocity, m/s (ft/s)	1.3–14.1 (4.3–46.3)	1.4–15.6 (4.7–51.1)	1.4–15.5 (4.6–51.0)
$T_{w,avg}$, H_2O temperature, K ($^{\circ}\text{F}$)	302.2–309.8 (84.3–97.9)	297.4–310.4 (75.7–99.0)	295.4–310.4 (72.1–99.1)
h_c^* , composite heat transfer coefficient, $\text{W}/\text{m}^2 \cdot \text{K}$ ($\text{Btu}/\text{h} \cdot \text{ft}^2 \cdot ^{\circ}\text{F}$)	5,780–6,920 (1,020–1,220)	5,900–10,770 (1,040–1,900)	6,240–12,020 (1,100–2,120)
ΔT_c^* , composite temperature difference, K ($^{\circ}\text{F}$)	1.7–3.1 (3.1–5.6)	1.6–3.1 (2.8–5.5)	1.4–2.9 (2.6–5.3)
RF, reflux ratio ($F_{N,i}/F_{N,e}$)	1.1–2.7	1.4–5.7	3.1–12.6

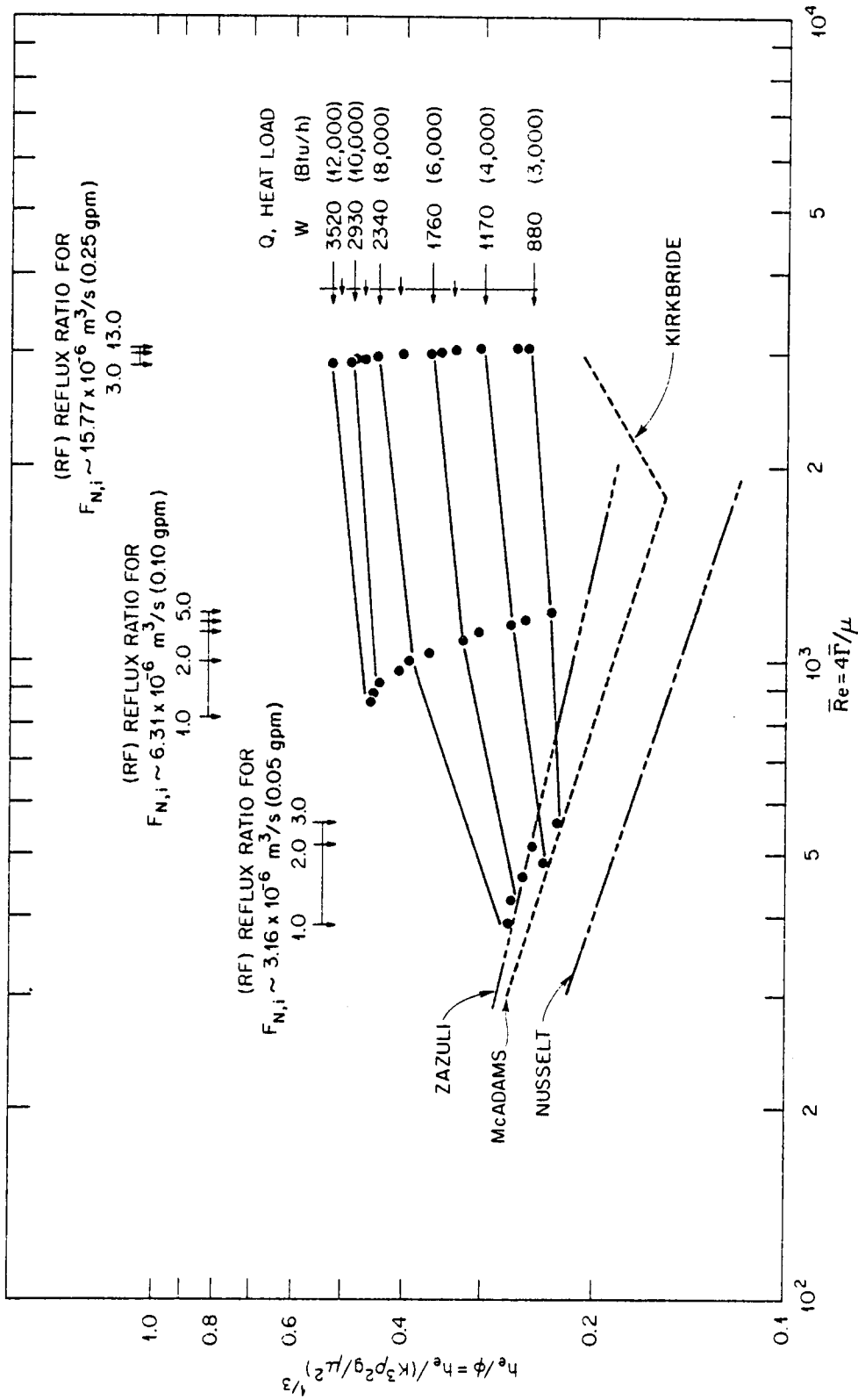


Fig. 6.1. Vertical smooth tube A evaporation results for ammonia — standard nondimensional coordinates with heat load and reflux ratio comparisons.

where ϕ is a normalizing factor, and h_e is the evaporation-side heat transfer coefficient [the composite heat transfer coefficient (h_c^*) with the tube wall resistance eliminated by the use of Eqs. (5.6) and (5.7)]. All ammonia fluid properties (k , ρ , and μ) were evaluated at the evaporator module outlet temperature $T_{N,out}$. During steady-state operation, the inlet $T_{N,in}$ and outlet $T_{N,out}$ ammonia temperatures differed by, at most, 1.1 K (2.0°F). Since fluid properties vary little over this temperature range, evaluating them at the evaporator module ammonia outlet temperature introduced negligible error. Also presented are cross-plots (Fig. 6.1) of constant heat load Q and reflux ratio defined by

$$RF = \frac{F_{N,in}}{(F_{N,in} - F_{N,out})} = \frac{F_{N,in}}{F_{N,e}}, \quad (6.3)$$

which represents the ratio of the ammonia feed rate to the corresponding evaporation rate. The ammonia inlet volume flow rate is $F_{N,in}$; the outlet volume flow rate is $F_{N,out}$; and the volume rate of evaporation is $F_{N,e}$.

Evaporation heat transfer coefficients h_e generally increase with increasing heat load Q and with increasing ammonia feed rates $F_{N,i}$ supplied to the tube top (Fig. 6.1). The results from smooth tube experiments lie considerably above the Nusselt⁹ (analytical) prediction. The semiempirical correlation of McAdams,¹⁷ and a correlation by Zazuli,¹⁰ which purports to account for ripple effects in the liquid film, are in good agreement with the smooth tube data at low heat loads and film Reynolds numbers. At higher film Reynolds numbers where film flow becomes turbulent, and at higher heat loads where bubble nucleation and boiling phenomena become visually pronounced, the existing correlations severely

underpredict the experimental data. These results suggest that some method other than the Nusselt analysis must be used for predicting evaporation heat transfer coefficients. One possible approach may be that suggested by Bergles and Rohsenow¹³ and reported by Lorenz and Yung:¹⁴ the heat transfer coefficient is the sum of contributions due to boiling and convection components [Eqs. (2.3), (2.5), (2.6), and (2.7)].

Smoothed Wilson-plot results for smooth Tube A are presented on composite heat transfer coefficient h_c^* vs heat load Q basis (Fig. 6.2) and on a heat load Q vs composite temperature difference ΔT_c^* basis (Fig. 6.3). Smoothed Wilson-plot values refer to the resultant average of several Wilson-plot combinations at a given heat load (Appendix A). Composite heat transfer coefficients increase with increasing heat loads and with increasing ammonia feed rates (Fig. 6.2), reaching a maximum of 12,020 W/m²·K (2120 Btu/h·ft²·°F) at a heat load of 3500 W (11,950 Btu/h) and an ammonia feed rate of 15.7×10^{-6} m³/s (0.249 gal/min). Figure 6.3 illustrates that, for a given composite temperature difference, the heat load increases with increasing ammonia feed rates.

6.2 Externally Fluted Tube F

Parameter ranges for ammonia evaporating on the outside of tube F (smooth inside surfaces and 48 external flutes) are given in Table 6.2. A total of 187 experimental runs, providing 22 heat transfer data points, were made at three different ammonia feed rates. A 1/2-in.-diam rod was inserted along the axis on the inside of tube F to (1) decrease the hydraulic diameter D_h , (2) increase the water velocity V_w for a given volume flow rate F_w , and (3) increase the water-side heat transfer coefficient h_w . This was done as a precautionary measure in the event that

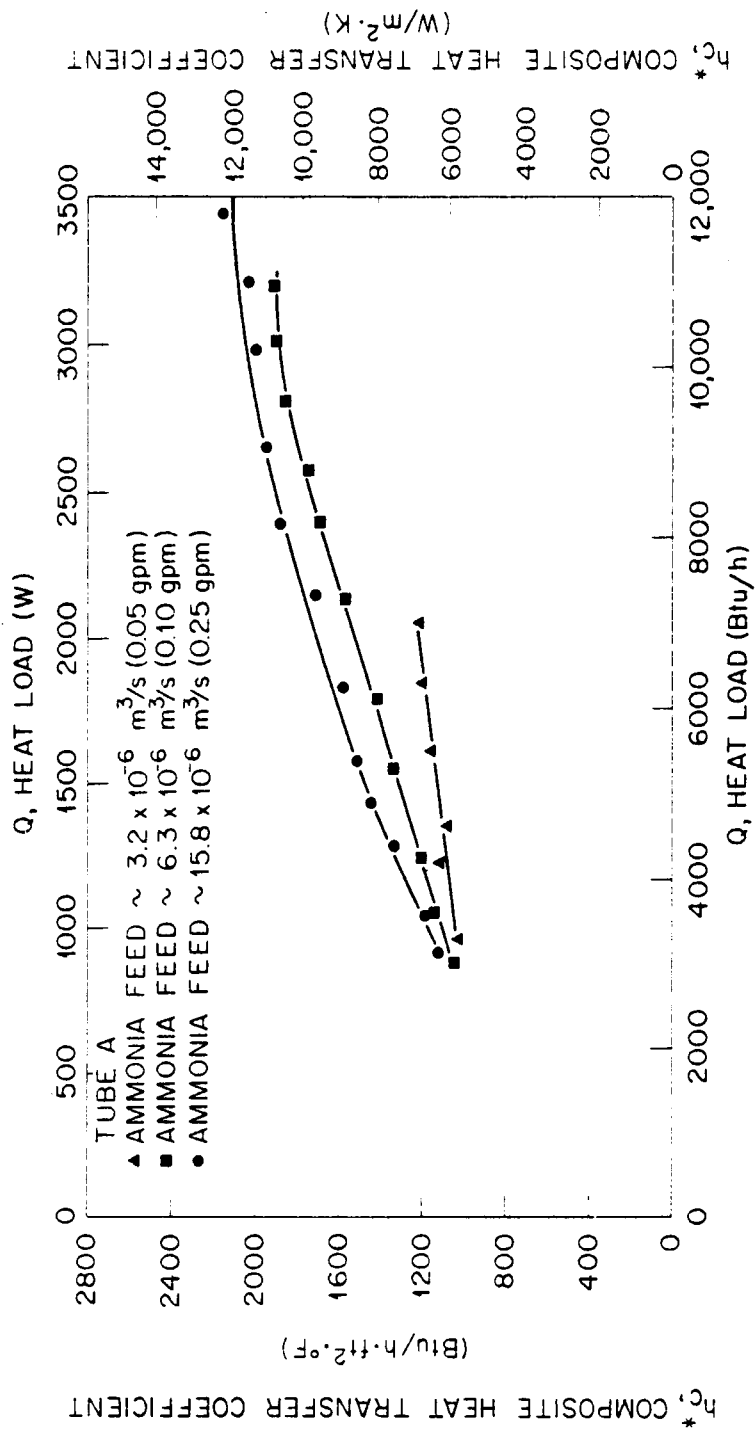


Fig. 6.2. Smoothed Wilson-plot results for smooth tube A on composite heat transfer coefficient vs heat load basis.

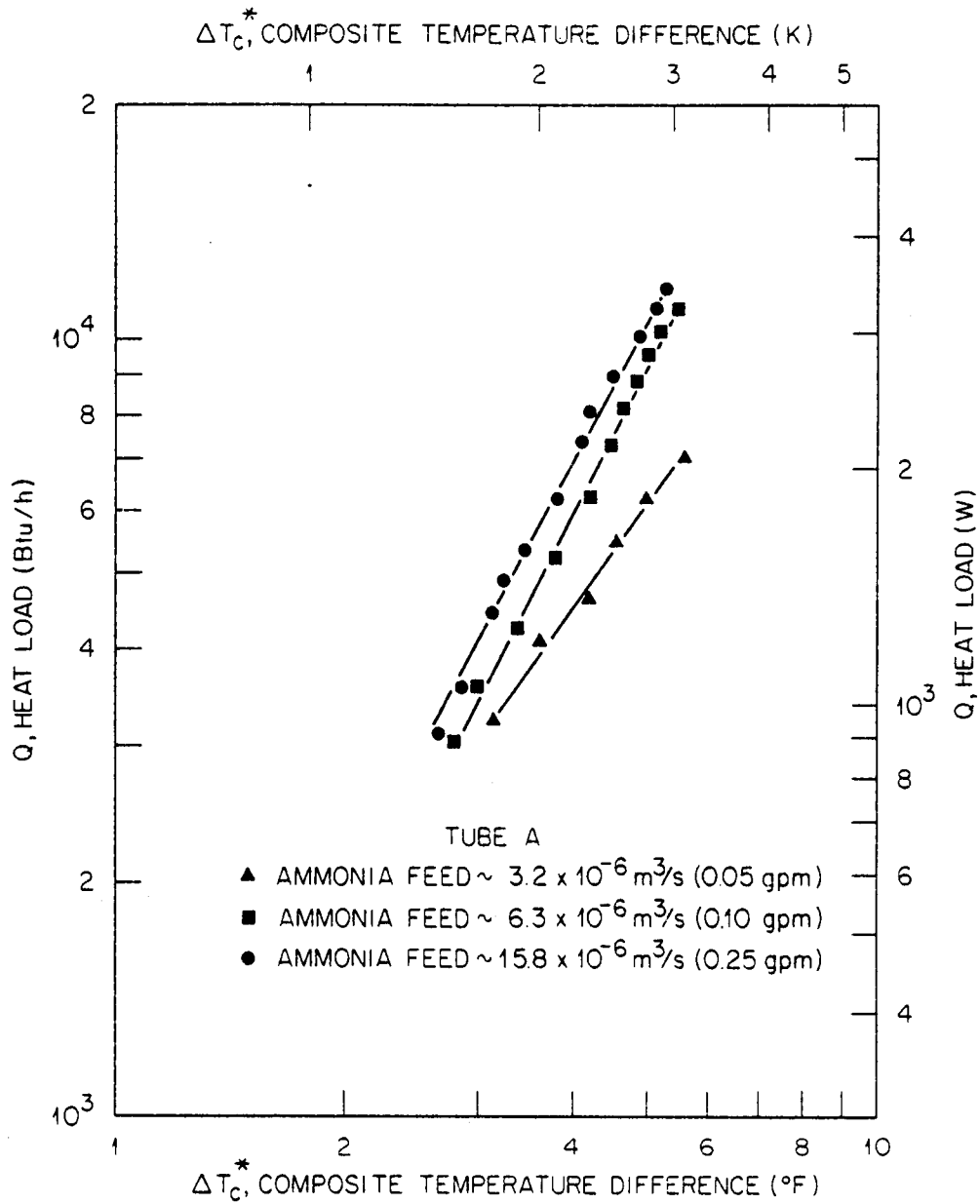


Fig. 6.3. Smoothed Wilson-plot results for smooth tube A on heat load vs composite temperature difference basis.

Table 6.2. Parameter ranges for externally fluted tube F

Parameters	Externally fluted tube F (48 flutes) [Total outside surface area, $A_{t,o} = 0.09643 \text{ m}^2 (1.038 \text{ ft}^2)$]		
	39	82	66
Number of runs	39	82	66
$F_{N,i}$, NH_3 feed rate, $\text{m}^3/\text{s} \times 10^6$ (gal/min)	3.186–3.356 (0.0505–0.0532)	6.353–6.385 (0.1007–0.1012)	15.596–15.766 (0.2472–0.2499)
Q , heat load, W (Btu/h)	880–2,050 (2,990–7,010)	690–3,190 (2,360–10,900)	880–3,990 (2,990–13,620)
$T_{N,o}$, NH_3 temperature, K ($^{\circ}\text{F}$)	299.0–301.7 (78.6–83.4)	298.9–303.5 (78.3–86.6)	297.2–305.9 (75.3–91.0)
F_w , H_2O flow rate, $\text{m}^3/\text{s} \times 10^2$ (gal/min)	5.2–40.1 (8.2–63.5)	4.7–42.6 (7.4–67.5)	5.1–42.8 (8.1–67.8)
V_w , H_2O velocity, m/s (ft/s)	1.8–14.1 (6.0–46.3)	1.6–15.0 (5.4–49.2)	1.8–15.1 (5.9–49.5)
$T_{w,avg}$, H_2O temperature, K ($^{\circ}\text{F}$)	301.7–314.4 (83.3–106.2)	300.8–314.0 (81.8–105.6)	298.9–315.3 (78.3–107.8)
h_c^* , composite heat transfer coefficient, $W/\text{m}^2 \cdot K$ (Btu/h $\cdot$ ft $^2 \cdot ^{\circ}\text{F}$)	3,690–4,540 (650–800)	5,330–7,030 (940–1,240)	7,650–10,660 (1,350–1,880)
ΔT_c^* , composite temperature difference, K ($^{\circ}\text{F}$)	2.0–5.7 (3.6–10.2)	1.7–4.7 (3.1–8.5)	1.3–3.2 (2.3–5.8)
RF, reflux ratio ($F_{N,i}/F_{N,e}$)	1.1–2.6	1.4–6.4	2.7–12.6

evaporation-side heat transfer coefficients were very large. Water-side heat transfer coefficients become more dominant (a larger fraction of the total overall resistance to heat flow) as evaporation-side heat transfer coefficients increase (decreasing resistance to heat flow), thus making evaluation of evaporation-side coefficients more difficult and less accurate.

Quite unexpectedly, results from experimental runs with tube F were in the same range as results from experimental runs with tube A. Thus, the concern about the dominance of water-side coefficients was unwarranted. Smoothed Wilson-plot results for fluted tube F are presented on a composite heat transfer coefficient h_c^* vs heat load Q basis (Fig. 6.4) and on a heat load Q vs composite temperature difference ΔT_c^* basis (Fig. 6.5). The composite heat transfer coefficient reaches a maximum of 10,660 W/m²·K (1880 Btu/h·ft²·°F) at the highest ammonia feed rate, 15.7×10^{-6} m³/s (0.250 gal/min), and at the highest heat load, 3990 W (13,620 Btu/h), tested. At the intermediate ammonia feed rate, the composite heat transfer coefficient increases as the heat load is increased from 690 W (2360 Btu/h) to 2000 W (7000 Btu/h), and decreases with further heat load increases. At the lowest ammonia feed rate, the composite heat transfer coefficient consistently decreases as the heat load is increased over the range tested. A possible explanation for such decreasing coefficients is that an increasing amount of the heat transfer tube surface is drying, and the wavy film heat transfer phenomena are not present under conditions of low ammonia feed rates and high heat load.

For a given composite temperature difference, the heat load increases with increasing ammonia feed rates (Fig. 6.5), similar to smooth tube results (Fig. 6.3). Based on heat load, comparisons of Fig. 6.2 to Fig. 6.4

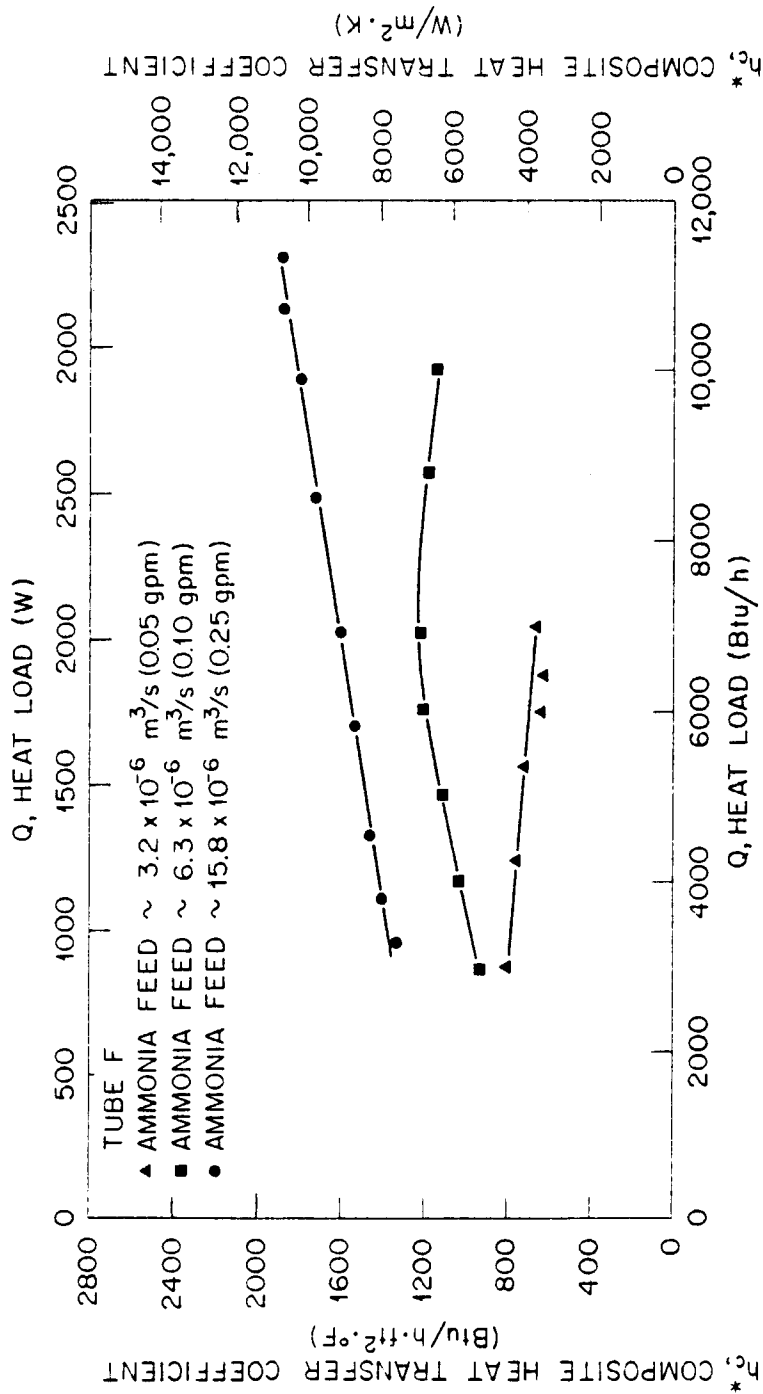


Fig. 6.4. Smoothed Wilson-plot results for externally fluted tube F on composite heat transfer coefficient vs heat load basis.

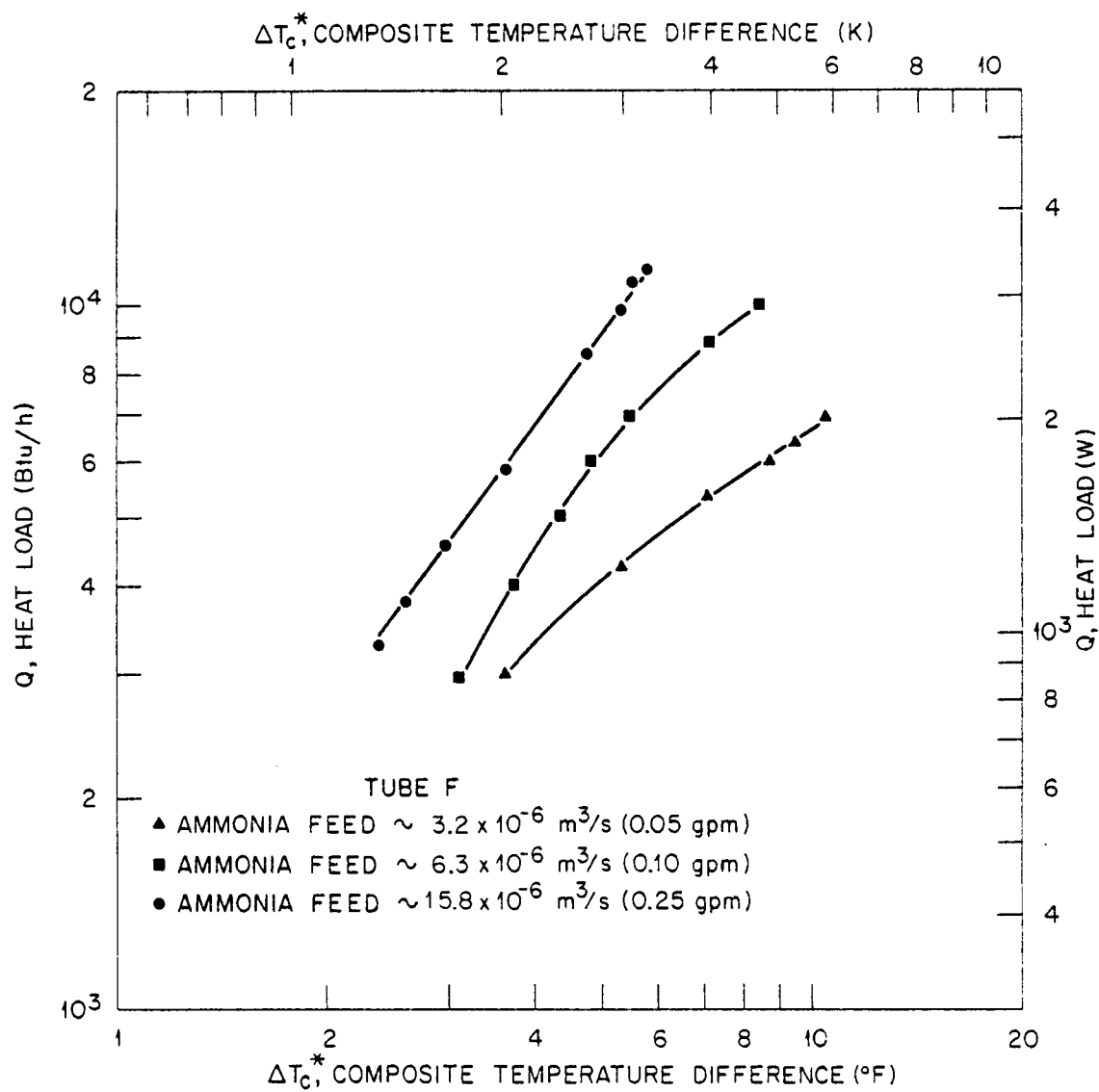


Fig. 6.5. Smoothed Wilson-plot results for externally fluted tube F on heat load vs composite temperature difference basis.

and Fig. 6.3 to Fig. 6.5 suggest that the heat transfer performance is similar at the highest feed rate tested, but that smooth tube A is superior at lower feed rates. Apparently under conditions of low ammonia feed rates, either the flute crests of tube F are drying out (reducing the tube heat transfer surface area), while the smooth surface of tube A remains wet, or different heat transfer mechanisms are present on the geometrically different tubes where the fluted tube does not remain completely wet.

6.3 Doubly Fluted Tube H

Parameter ranges for ammonia evaporating on the outside of doubly fluted tube H (42 external and 34 internal flutes) are given in Table 6.3. A total of 186 experimental runs, providing 29 heat transfer data points, were made at the three different ammonia feed rates. Smoothed Wilson-plot results for doubly fluted tube H are presented on a composite heat transfer coefficient vs heat load basis (Fig. 6.6) and on a heat load vs composite temperature difference basis (Fig. 6.7).

Composite heat transfer coefficients remained relatively constant over the heat load range tested (Fig. 6.6). For a given heat load, the highest composite heat transfer coefficient is obtained with the intermediate ammonia feed rate (except at very high heat loads where ammonia film dryout conditions are approached), followed closely by results from the highest feed rate. Minimum values of the composite heat transfer coefficient were obtained at the lowest feed rate tested. A possible explanation for the intermediate feed rate providing the highest coefficients (unlike results from tube A and tube F tests) is that the intermediate

Table 6.3. Parameter ranges for doubly fluted tube H

Parameters	Doubly fluted tube H (42 external/34 internal flutes) [Total outside surface area, $A_{t,o} = 0.16165 \text{ m}^2 (1.740 \text{ ft}^2)$]		
	41	78	65
Number of runs			
$F_{N,i}$, NH_3 feed rate, $\text{m}^3/\text{s} \times 10^6$ (gal/min)	3.271–3.290 (0.0518–0.0521)	6.359–6.423 (0.1008–0.1018)	15.702–15.860 (0.2489–0.2514)
Q , heat load, W (Btu/h)	750–2,120 (2,560–7,230)	890–3,690 (3,050–12,600)	910–3,750 (3,090–12,790)
$T_{N,o}$, NH_3 temperature, K ($^{\circ}\text{F}$)	301.3–304.7 (82.7–88.8)	300.6–308.3 (81.4–95.3)	301.9–310.0 (83.8–98.4)
F_w , H_2O flow rate, $\text{m}^3/\text{s} \times 10^2$ (gal/min)	5.1–65.7 (8.0–88.2)	5.1–65.9 (8.0–88.5)	5.2–65.4 (8.2–87.8)
V_w , H_2O velocity, m/s (ft/s)	1.2–13.1 (3.9–43.0)	1.2–13.2 (3.9–43.2)	1.3–13.1 (4.0–42.9)
T_w , avg, H_2O temperature, K ($^{\circ}\text{F}$)	302.4–313.0 (84.7–103.7)	301.8–315.9 (83.5–108.9)	303.7–317.3 (86.9–111.4)
h_c^* , composite heat transfer coefficient, $\text{W}/\text{m}^2\cdot\text{K}$ ($\text{Btu}/\text{h}\cdot\text{ft}^2\cdot^{\circ}\text{F}$)	2,720–3,290 (480–580)	4,650–6,290 (820–1,110)	3,630–6,800 (640–1,200)
ΔT_c^* , composite temperature difference, K ($^{\circ}\text{F}$)	1.9–3.8 (3.4–6.9)	1.2–3.6 (2.2–6.5)	1.7–3.5 (3.1–6.3)
RF, reflux ratio ($F_{N,i}/F_{N,e}$)	1.1–3.0	1.2–4.9	2.8–10.8

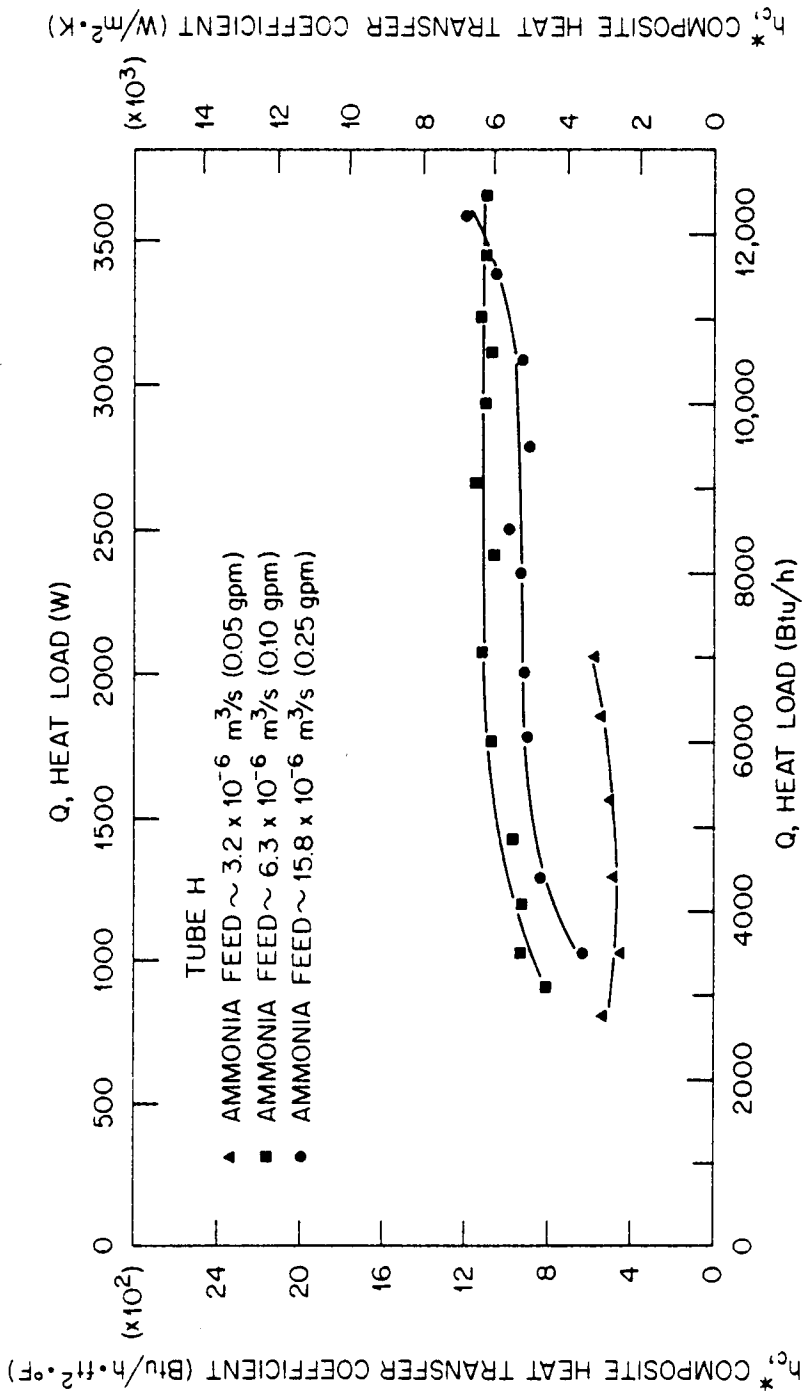


Fig. 6.6. Smoothed Wilson-plot results for doubly fluted tube H on composite heat transfer coefficient vs heat load basis.

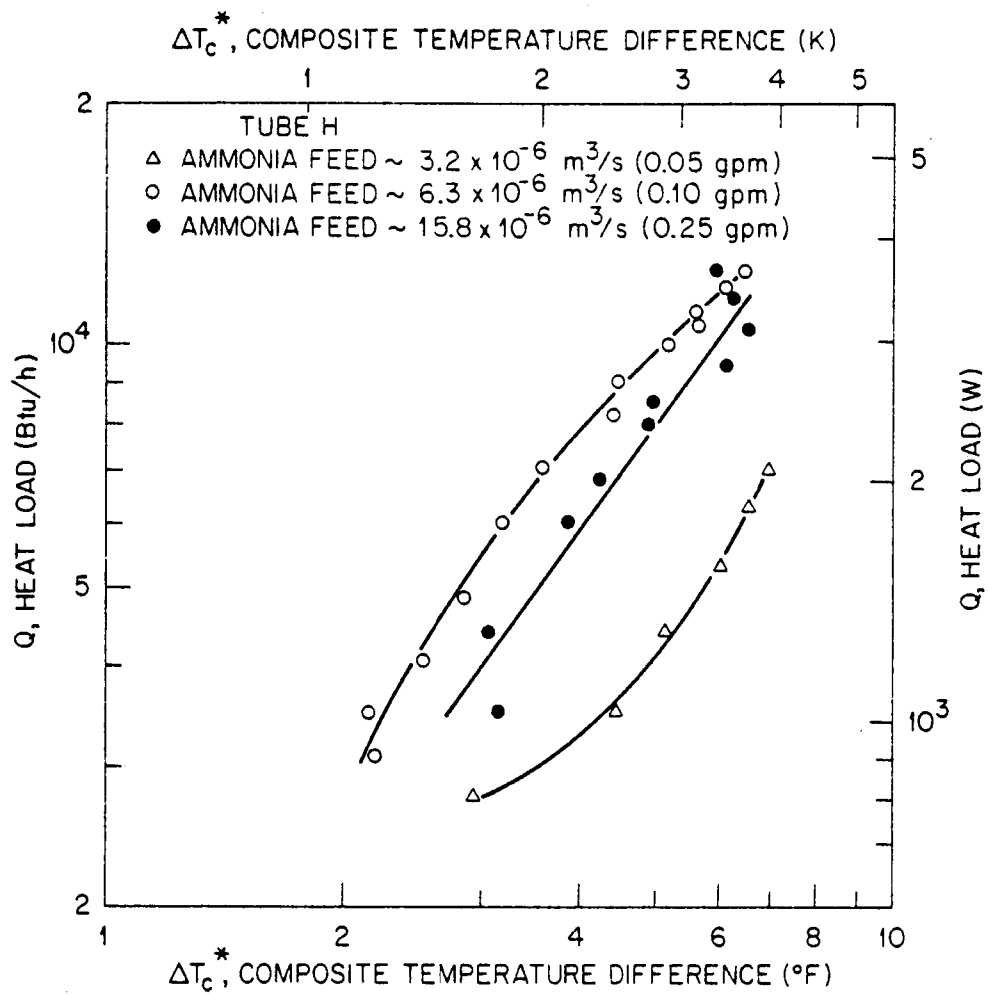


Fig. 6.7. Smoothed Wilson-plot results for doubly fluted tube H on heat load vs composite temperature difference basis.

feed rate may provide the more optimum film thickness for boiling in the relatively deep troughs of tube H.

At higher ammonia feed rates (turbulent flow), a large volume of liquid occupies each flute trough. As liquid ammonia flows down the tube, superheated liquid near the tube wall is displaced by cooler liquid falling near the outside layer of the film. This mixing action possibly interrupts the layer of superheated film near the tube wall, thus suppressing boiling. At the lowest feed rate tested, only a small portion of the tube surface (the bottom of the flute troughs) is wet by liquid ammonia. Since the bottom of the flute trough represents a small portion of the total tube surface area, little heat is transferred. At the intermediate ammonia feed rate, most of the tube wall is bathed in fluid. Since the feed rate is in the laminar flow range, mixing of the superheated ammonia film near the tube wall and the cooler liquid near the outside layer of the film does not occur. Thus, a relatively undisturbed superheated film layer develops near the tube wall, providing conditions necessary for boiling. Since the intermediate ammonia feed rate for tube H provides more ideal conditions for boiling, and since boiling is recognized as an efficient means of heat transfer, highest coefficients were obtained at this feed rate.

Although the composite heat transfer coefficients for a given heat load (Fig. 6.6) are lower than those obtained from tube A (Fig. 6.2) and tube F (Fig. 6.4), results for tube H (Fig. 6.7) are of the same magnitude as from tube A (Fig. 6.3) and tube F (Fig. 6.5), when compared on a composite temperature difference vs heat load basis. This result is due to the much larger surface area available on tube H. As previously mentioned

the surface area of tube H is not completely utilized for transferring heat because of the deep flute troughs. Ammonia liquid is channeled into the troughs, leaving the flute crests at, or near, dryout conditions. When heat transfer performance is evaluated with the area factor removed (Figs. 6.3, 6.5, and 6.7), results are of the same magnitude.

6.4 Comparison of Results from Tubes A, F, and H

The heat transfer performance of each tube tested may be compared in Figs. 6.8, 6.9, and 6.10, where results are presented on a heat load vs composite temperature basis. At a constant ammonia feedrate of $\sim 3.2 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm) as shown in Fig. 6.8, higher heat loads can be obtained with tube A at a given composite temperature difference than with either tube F or tube H. At this feedrate, the poorest performance was obtained with tube F at high heat loads.

At the intermediate ammonia feedrate of $\sim 6.3 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm), as presented in Fig. 6.9, the poorest heat transfer performance was again obtained from tube F. Over most of the heat load range, the best results were obtained with tube H. Only at the highest heat loads did the performance of tube A match or exceed that obtained from tube H.

Figure 6.10 presents results obtained at the highest ammonia feedrate tested, $\sim 15.8 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm). The performance of each tube was nearly identical over the entire heat load range. Only at the highest heat loads did tube A slightly outperform tube F and tube H. Thus, from the above discussion, the best overall performance was obtained from smooth tube A over the heat load and ammonia feedrate range covered in this experimental study.

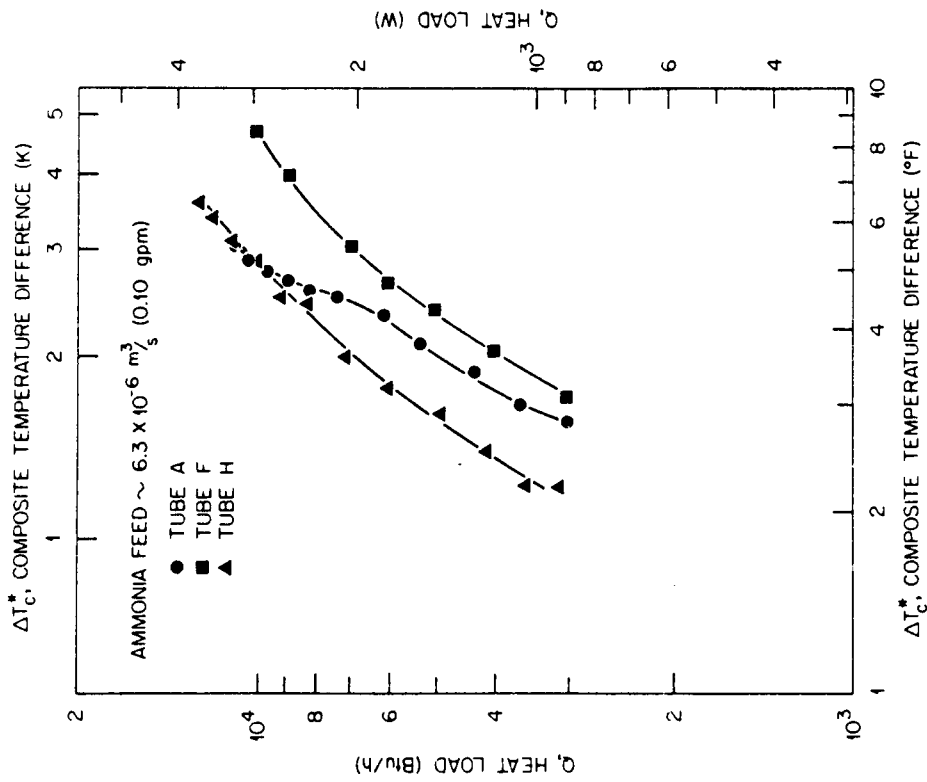


Fig. 6.9. Smoothed Wilson-plot results for tubes A, F, and H at an ammonia feedrate of $\sim 6.3 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm) on a heat load vs composite temperature difference basis.

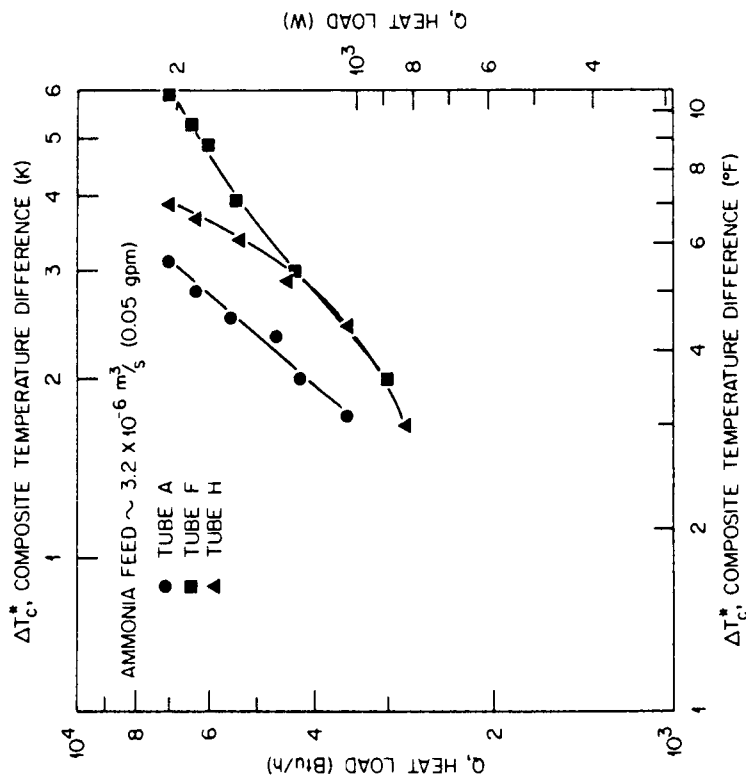


Fig. 6.8. Smoothed Wilson-plot results for tubes A, F, and H at an ammonia feedrate of $\sim 3.2 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm) on a heat load vs composite temperature difference basis.

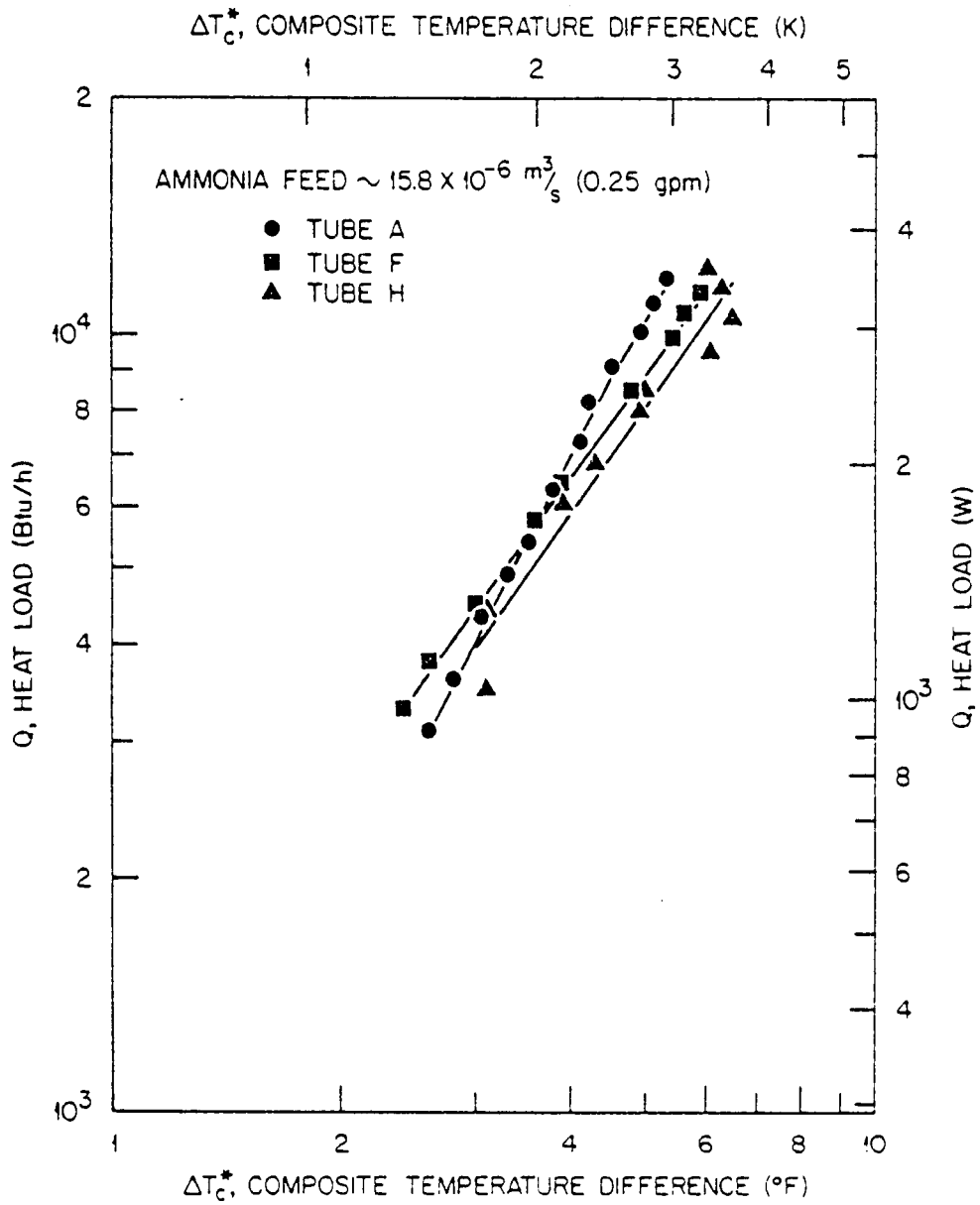


Fig. 6.10. Smoothed Wilson-plot results for tubes A, F, and H at an ammonia feedrate of $\sim 15.8 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm) on a heat load vs composite temperature difference basis.

6.5 Photographic Study

High-speed motion pictures (2500 frames/s) of the ammonia evaporation process were made for each tube tested. With the aid of lighting in suitable locations, the process was filmed through the viewport located on the evaporator shell. Figure 6.11 presents ten photographs reproduced from individual frames of one motion picture. Each photograph represents an elapsed time of 0.004 s from the previous photograph in the sequence. Experimental conditions for tube A at the time of filming were

Heat load: 3520 W (12,000 Btu/h),

Ammonia feed rate: $15.515 \times 10^{-6} \text{ m}^3/\text{s}$ (0.2458 gal/min),

Ammonia temperature: 303.0 K (85.7°F).

As shown in picture 1 of Fig. 6.11, many small bubbles appear that are similar in appearance to a foam or froth. This foamy appearance passes, followed by several large bubbles (pictures 5 through 10). The alternation of the presence of foam followed by several large bubbles was a typical occurrence, as evidenced by viewing the motion picture of the evaporation processes on tube A. Similar results were not seen on the motion pictures of evaporation processes on tubes F and H.

Photographic sequences of ammonia evaporation on tubes F and H are not presented here because of the difficulty in viewing the evaporation process from still photographs. Under similar experimental conditions, evaporation on tube F produced bubbles both on the flute crests and in the flute troughs. All bubbles were small in diameter compared to those on tube A. Bubbles were again small for tube H but were confined to the flute troughs. The flute crests of tube H were often dry. Unlike the evaporation process seen in the motion pictures of tube A, no foam or froth formation was seen on tubes F and H.

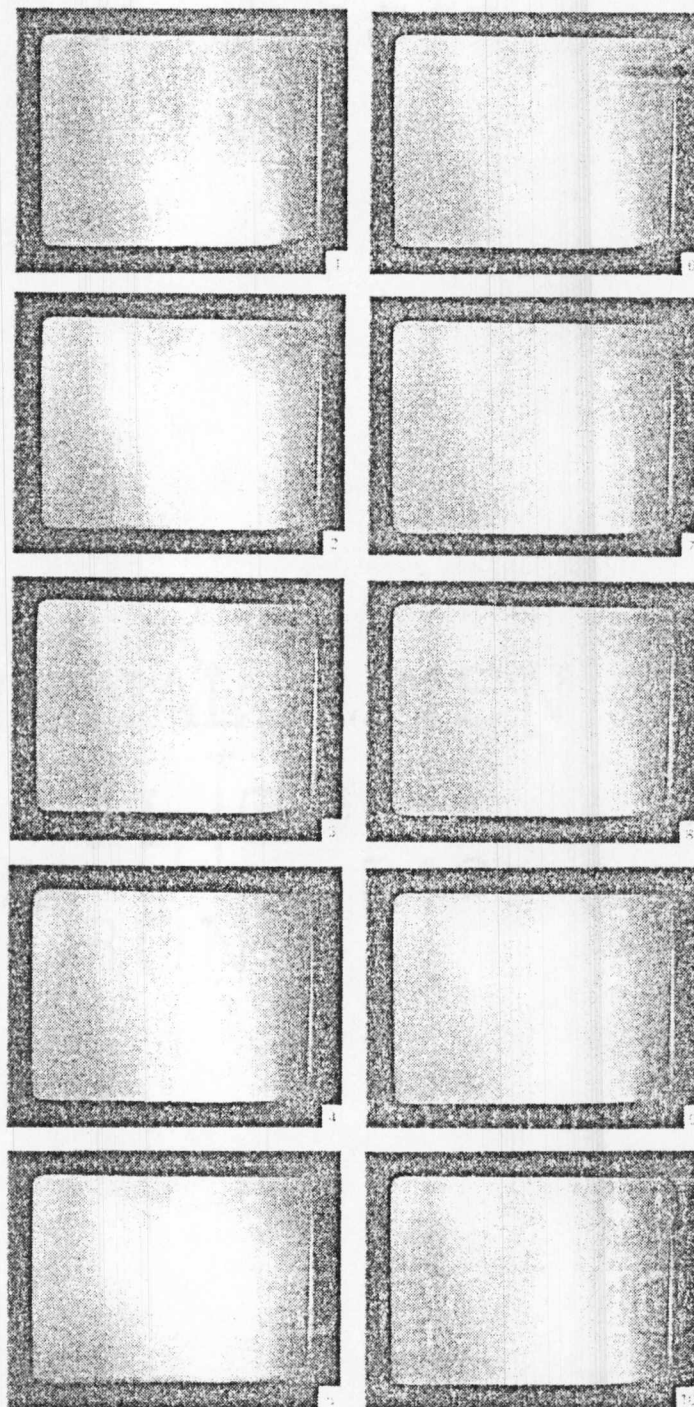


Fig. 6.11. Photographic study of ammonia evaporation on tube A.

7. CONCLUSIONS

The following conclusions were drawn from the experimental study for ammonia evaporation on the outside of single vertical tubes:

1. Over the experimental test ranges covered in this study, the heat transfer performance of the smooth tube was superior to that of either of the fluted tubes tested. Unlike the fluted tubes, a foam or froth appeared in the ammonia film during the evaporation process on the smooth tube. Upon passage of the foam down the tube wall, many large bubbles formed. The alternation of the presence of foam and large bubbles apparently was an important heat transfer mechanism for the smooth tube, but not for the fluted tubes.

2. At low ammonia feed rates, the fluted tube geometry was actually detrimental to heat transfer. Under these conditions, the flute crests were not bathed in liquid, thus making a portion of the tube surface area unavailable for transferring heat to the ammonia. Bubbles formed and remained only in the liquid ammonia which, in turn, was confined to the flute troughs. At low ammonia feed rates on the smooth tube, the entire surface was covered with a thin film and many bubbles. Therefore, the smooth tube was more efficient in utilizing its available surface area for boiling and transferring heat.

3. As suggested in Fig. 6.1, ammonia evaporation heat transfer coefficients are a function of both the liquid film Reynolds number and the heat duty. Analytical predictions for evaporation heat transfer coefficients (using Nusselt analysis) underpredict experimental results. An approach similar to that used by Bergles and Rohsenow¹³ may be

necessary to account for contributions due to boiling. This boiling term may be simply added to the convection heat transfer terms. If it is assumed that the evaporation heat transfer coefficient does consist of a convection term and a boiling term, and if it is assumed that correlations sufficiently predict the convection term, then the boiling term is strongly dependent on the heat duty and film Reynolds number (Fig. 6.1).

Further conclusions may be determined for this study, provided that the OTEC experimental program continues at ORNL and that supplemental information is obtained.

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APPENDICES

Appendix A

SAMPLES OF DATA REDUCTION

A.1 Physical Properties for Ammonia

All property data for ammonia used in data reduction were taken from ASHRAE handbooks^{15,20} where ammonia is designated as R-717. The accuracy of thermophysical properties is discussed in Ref. 20.

A.2 Fluted Tube

A sample summary of experimental data required for computing the heat transfer rates and coefficients in the evaporator module is listed in Table A.1. The data are for thin film evaporation of ammonia on the outside of fluted tube F (48 external corrugations) for a constant ammonia feed rate of 0.248 gpm. Experimental run R-717-260F is used to demonstrate the data reduction procedure while the series of runs R-717-260F through R-717-265F is used to illustrate the Wilson-plot technique.

Table A.1. Sample of experimental data — ammonia
evaporating outside externally fluted tube F

Run No.	$F_{N,in}$ (gpm)	$T_{N,out}$ (°F)	F_w (gpm)	V_w (ft/s)	$T_{w,avg}$ (°F)	ΔT_w (°F)	RF	Q (Btu/h)
R-717-260F	0.2482	81.3642	46.2	33.7	87.8837	0.3615	4.5	8309
R-717-261F	0.2483	81.7926	18.8	13.7	90.6720	0.9010	4.4	8411
R-717-262F	0.2482	81.2653	66.8	48.7	87.4893	0.2550	4.4	8479
R-717-263F	0.2483	81.8441	28.1	20.5	89.5747	0.6059	4.4	8484
R-717-264F	0.2484	82.0713	9.4	6.8	93.9051	1.8563	4.3	8664
R-717-265F	0.2481	80.6281	38.2	27.9	87.5996	0.4619	4.2	8786

In this study, the inlet and outlet temperatures $T_{w,in}$ and $T_{w,out}$ were actually measured and used to determine the average water temperature $T_{w,avg}$ and the change in the water temperature ΔT_w . Only the calculated values of $T_{w,avg}$ and ΔT_w are given in the tables present in this report because of space limitations and because these variables are commonly used in further calculations. The actual measured values of $T_{w,in}$ and $T_{w,out}$, the inlet and outlet water temperatures in the evaporator module can be determined from:

$$T_{w,in} = T_{w,avg} + \Delta T_w / 2 , \quad (A.1)$$

$$T_{w,out} = T_{w,avg} - \Delta T_w / 2 , \quad (A.2)$$

with the information for run R-717-260F,

$$T_{w,in} = (87.8837^\circ\text{F}) + (0.3615^\circ\text{F}/2) = 88.0645^\circ\text{F} ,$$

$$T_{w,out} = (87.8837^\circ\text{F}) - (0.3615^\circ\text{F}/2) = 87.7030^\circ\text{F} .$$

The heat transfer rate or heat load in the evaporator module can be computed from

$$Q = \dot{m}_w c_{p,w} \Delta T_w , \quad (5.3)$$

where the water mass flow rate is given by

$$\dot{m}_w = F_w \rho_w . \quad (5.4)$$

The values of heat capacity $c_{p,w}$ and density ρ_w of the primary evaporator heating water are calculated at the average temperature of the primary

water $T_{w,avg}$. In this particular example, the change in water temperature ΔT_w is so small that the variation in properties is insignificant. The properties for water at an average temperature of 87.8837°F are:

$$\rho_w \cong 62.0 \text{ lbm/ft}^3, \quad c_{p,w} = 1.0 \text{ Btu/lbm}^\circ\text{F}$$

so that the heat transfer rate for run R-717-260F becomes,

$$\begin{aligned} Q &= (46.2 \text{ gal/min})(62.0 \text{ lbm/ft}^3)(1.0 \text{ Btu/lbm}^\circ\text{F})(0.3615^\circ\text{F}) \\ &\quad \times (0.1337 \text{ ft}^3/\text{gal})(60 \text{ min/h}) \\ &= 8309 \text{ Btu/h} . \end{aligned}$$

The mass rate of ammonia evaporation for a given heat transfer rate is

$$\dot{m}_{N,e} = \frac{Q}{h_{fg}} . \quad (\text{A.4})$$

For saturated ammonia at 81.3642°F , the latent heat of vaporization and the liquid density is given by

$$h_{fg} \cong 497.3 \text{ Btu/lbm} , \quad \rho_N = 37.4 \text{ lbm/ft}^3 .$$

The mass rate of evaporation is

$$\begin{aligned} \dot{m}_{N,e} &\cong \frac{8309 \text{ Btu/h}}{497.3 \text{ Btu/lbm}} \\ &\cong 16.7 \text{ lbm/h} , \end{aligned}$$

and the volume rate of ammonia evaporation is

$$\begin{aligned} F_{N,e} = \frac{\dot{m}_{N,e}}{\rho_N} &\cong \left(\frac{16.7 \text{ lbm/h}}{37.4 \text{ lbm/ft}^3} \right) \left(\frac{\text{h}}{60 \text{ min}} \right) \left(\frac{\text{gal}}{0.1337 \text{ ft}^3} \right) \\ &= 0.0557 \text{ gal/min} . \end{aligned}$$

The reflux ratio RF is the ratio of the ammonia feed rate at the top of the tube to the amount of ammonia which evaporates or

$$RF = \frac{F_{N,i}}{F_{N,e}} . \quad (6.3)$$

For run R-717-258F, the reflux ratio is:

$$\begin{aligned} RF &\cong \frac{0.2482 \text{ gal/min}}{0.0557 \text{ gal/min}} \\ &\cong 4.5 . \end{aligned}$$

The mean temperature difference $\overline{\Delta T}$ between the saturated liquid ammonia and the average temperature of the primary water is given by

$$\overline{\Delta T} = \left(\frac{T_{w,in} + T_{w,out}}{2} \right) - T_{N,o} . \quad (5.2)$$

The outlet liquid temperature is used in these calculations because it most closely represents the saturation temperature of the evaporating ammonia. With the information for run R-717-260F,

$$\begin{aligned} \overline{\Delta T} &= \left(\frac{88.0645^\circ\text{F} + 87.7030^\circ\text{F}}{2} \right) - 81.3642^\circ\text{F} \\ &= 6.5195^\circ\text{F} . \end{aligned}$$

The overall evaporation heat transfer coefficient, based on the total outside tube surface area $A_{t,o}$ can be calculated from,

$$U_o = \frac{Q}{A_{t,o} \overline{\Delta T}} , \quad (5.1)$$

which is

$$U_o \cong \frac{8309 \text{ Btu/h}}{(1.038 \text{ ft}^2)(6.5195^\circ\text{F})}$$

$$\cong 1228 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} .$$

The inverse of the overall coefficient is

$$1/U_o = 1/1228 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$$

$$= 0.0008145 (\text{Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F})^{-1} .$$

The water velocity through the tube inside may be calculated from

$$V_w = F_w/A_{i,cs} ,$$

where $A_{i,cs}$ is the cross-sectional flow area. During experimental tests with tube F, a 1/2-in.-diam rod was inserted through the tube center as noted in Sect. 7. For tube F tests, the cross-sectional flow area is

$$A_{i,cs} = \frac{\pi}{4} (D_i^2 - D_r^2) ,$$

or, since tube F has an inside diameter D_i of 0.90 in.,

$$A_{i,cs} = \frac{\pi}{4} \left[\left(\frac{0.90}{12} \right)^2 - \left(\frac{0.50}{12} \right)^2 \right]$$

$$= 0.003054 \text{ ft}^2 .$$

The average water velocity through tube F for a volume flow rate of 46.2

gpm, then, is

$$v_w = \left(\frac{46.2 \text{ gal/min}}{0.003054 \text{ ft}^2} \right) \left(0.1337 \frac{\text{ft}^3}{\text{gal}} \right) \left(\frac{\text{min}}{60 \text{ s}} \right)$$

$$= 33.7 \text{ ft/s} ,$$

and the water velocity to the negative 0.8 power ($1/v_w^{0.8}$) is

$$1/v_w^{0.8} = (1/33.7 \text{ ft/s})^{0.8}$$

$$= 0.0600 .$$

The calculations illustrated for run R-717-260F can be carried out on the other five runs in Table A.1. The results of calculations for all six runs are presented in Tables A.1 and A.2. Results presented in Table A.2 are used primarily for construction and evaluation of Wilson-plots. The values of the inverse of the overall coefficient and the water velocity raised to the 0.8 power for each run were used as data points to construct the Wilson-plot (Fig. A.1).

Three combinations of data points were used to construct Wilson-plots: (1) one including the series of runs, R-717-260F through R-717-263F; (2) one including the series of runs, R-717-262F through R-717-265F; and (3) one including the entire series of runs, R-717-260F through R-717-265F. Each series was fitted by a least-squares method of the first order to determine the best linear fit to satisfy the following relationship:

$$1/U_o = a_0 + a_1 v^{-0.8} , \tag{5.12}$$

where a_1 is the slope of the straight line and a_0 is the y-intercept.

The reciprocal ($1/a_0$ or h_c^*) gives the composite heat transfer coefficient

Table A.2. Sample Wilson-plot values — ammonia evaporating outside externally fluted tube F

Run No.	Q (Btu/h)	$\overline{\Delta T}$ (°F)	U_o (Btu/h·ft ² ·°F)	$1/U_o$	V_w (ft/s)	$(1/V_w)^{0.8}$
R-717-260F	8309	6.5195	1228	0.0008145	33.7	0.0600
R-717-261F	8411	8.8794	913	0.0010958	13.7	0.1234
R-717-262F	8479	6.2240	1313	0.0007619	48.7	0.0446
R-717-263F	8484	7.7306	1057	0.0009458	20.5	0.0892
R-717-264F	8664	11.8338	705	0.0014177	6.8	0.2148
R-717-265F	8786	6.9715	1214	0.0008236	27.9	0.0698

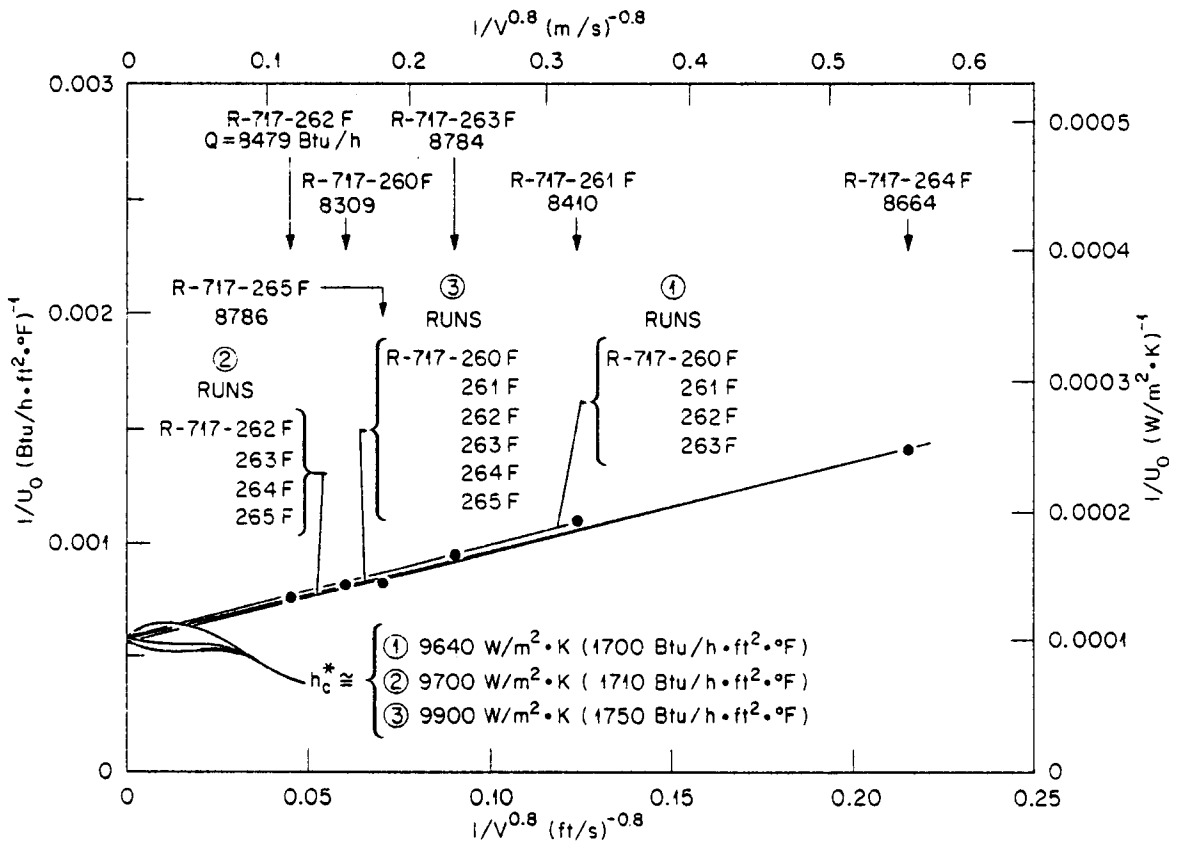


Fig. A.1. Wilson-plots for ammonia evaporation outside externally fluted tube F — runs R-717-260F to R-717-265F.

of the evaporating film and tube wall. The values a_o and h_c^* for each Wilson-plot are

$$(1) a_o = 5.88 \times 10^{-4}, \quad h_c^* = 1700;$$

$$(2) a_o = 5.85 \times 10^{-4}, \quad h_c^* = 1710;$$

$$(3) a_o = 5.71 \times 10^{-4}, \quad h_c^* = 1750.$$

The data show good linearity and allow extrapolation, with some confidence, to infinite water velocity (zero water-side resistance) at the plot y-intercept (Fig. A.1). The composite heat transfer coefficients obtained above average to a value of 1720 Btu/h·ft²·°F. The average heat load value is approximately 8500 Btu/h for this series of runs. The corresponding composite temperature difference is given by Eq. (5.9):

$$\Delta T_c^* = \frac{Q}{h_c^* A_o} = \frac{8500 \text{ Btu/h}}{(1720 \text{ Btu/h} \cdot \text{ft}^2 \cdot ^\circ\text{F})(1.038 \text{ ft}^2)} \approx 4.8^\circ\text{F}$$

Along with results from other experimental data, these smoothed or averaged Wilson-plot results are presented in graphical (Sect. 6) and tabular form (Appendix B).

A.3 Smooth Tube

A sample summary of experimental data required for computing the heat transfer rates for runs R-717-129A through R-717-133A is listed in Table A.3. The data are for thin film evaporation of ammonia on the outside of smooth tube A, for a constant ammonia feed rate of 0.052 gpm. The water

Table A.3. Sample of experimental data -- ammonia evaporating outside externally fluted tube A

Run No.	$F_{N,in}$ (gpm)	$T_{N,out}$ (°F)	F_w (gpm)	V_w (ft/s)	$T_{w,avg}$ (°F)	ΔT_w (°F)	RF	Q (Btu/h)
R-717-129A	0.0520	86.5365	25.1	13.6	93.3663	0.4270	1.4	5341
R-717-130A	0.0519	84.3156	84.8	45.8	89.9636	0.1301	1.4	5491
R-717-131A	0.0520	87.2107	11.7	6.3	96.8050	0.9622	1.4	5591
R-717-132A	0.0520	86.4060	41.2	22.2	92.6898	0.2734	1.4	5603
R-717-133A	0.0520	86.8907	14.1	7.6	96.1968	0.8181	1.3	5728

velocity through the tube inside may be calculated from

$$V_w = F_w / A_{i,cs} \quad (A.5)$$

For tube A, the inside diameter is 0.87 in. Thus, the cross-sectional flow area is

$$\begin{aligned}
 A_{i,cs} &= \frac{\pi}{4} \left(\frac{0.87 \text{ in.}}{12 \text{ in./ft}} \right)^2 \\
 &= 0.00413 \text{ ft}^2 ,
 \end{aligned}$$

and the water velocity for run R-717-129A is

$$\begin{aligned}
 V_w &= \left(\frac{25.1 \text{ gpm}}{0.00413 \text{ ft}^2} \right) \left(0.1337 \frac{\text{ft}^3}{\text{gal}} \right) \left(\frac{\text{min}}{60 \text{ s}} \right) \\
 &= 13.6 \text{ ft/s} .
 \end{aligned}$$

Other information used for determining the Wilson-plot values was selected in the same manner as previously explained for tube F. Sample information for the Wilson plot for runs R-717-129A through R-717-133A is presented in Table A.4. Smoothed or averaged results obtained from the Wilson plot

Table A.4. Sample Wilson-plot values -- ammonia evaporation outside smooth tube A

Run No.	Q (Btu/h)	$\overline{\Delta T}$ (°F)	U_o (Btu/h·ft ² ·°F)	1/ U_o	V_w (ft/s)	(1/ V_w) ^{0.8}
R-717-129A	5341	6.8297	747	0.0013387	13.6	0.1242
R-717-130A	5491	5.6481	929	0.0010770	45.8	0.0469
R-717-131A	5591	9.5944	557	0.0017967	6.3	0.2294
R-717-132A	5603	6.2837	852	0.0011743	22.2	0.0837
R-717-133A	5728	9.3061	588	0.0017011	7.6	0.1976

(Fig. A.2) are

$$Q = 5500 \text{ Btu/h} ,$$

$$h_c^* = 1150 \text{ Btu/h·ft}^2\text{·°F} ,$$

$$\Delta T_c^* = 4.5^\circ\text{F} .$$

Smoothed or averaged Wilson plot results for smooth tube A are presented in graphical (Sect. 6) and tabular form (Appendix B).

The individual evaporation-side heat transfer coefficient for smooth tube A can be computed by solving for h_e in Eq. (5.7):

$$1/h_c^* = 1/h_e + R_w , \quad (5.7)$$

or

$$h_e = \frac{1}{1/h_c^* - R_w} , \quad (A.6)$$

where R_{wall} is given by Eq. (5.6):

$$R_{wall} = \frac{r_o}{k} \ln \frac{r_o}{r_i} . \quad (5.6)$$

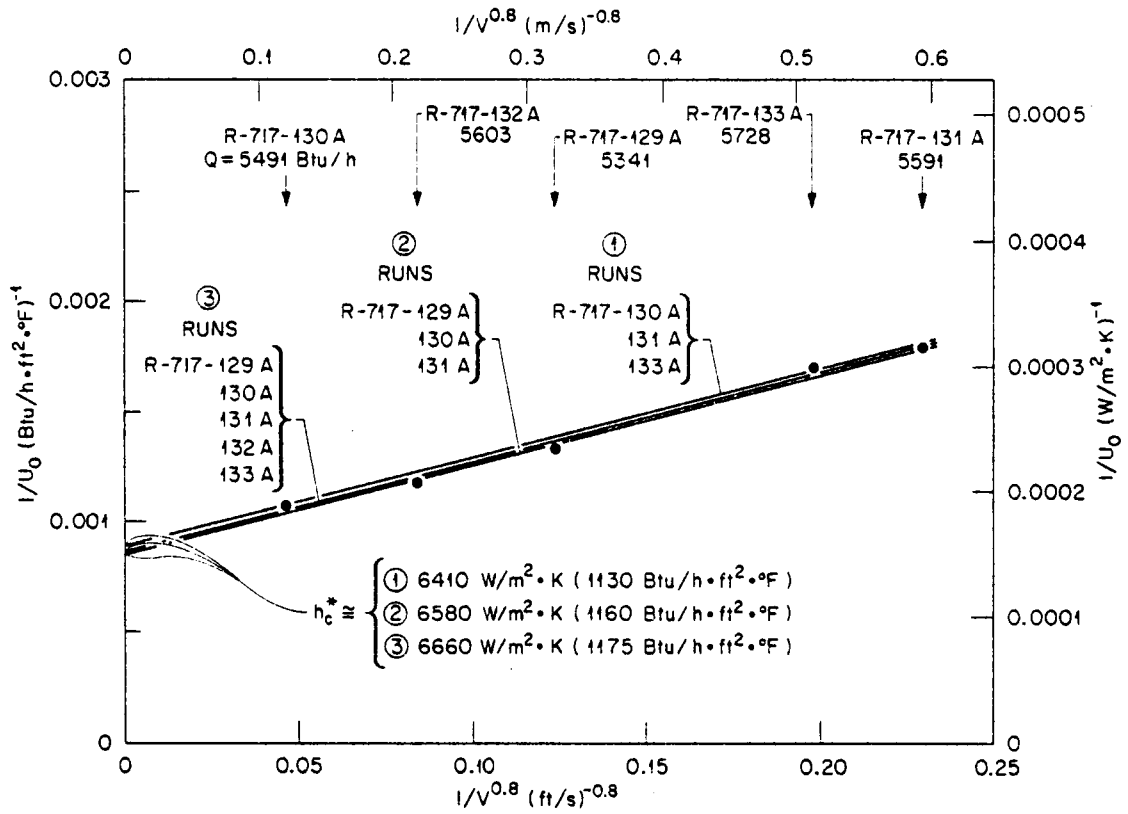


Fig. A.2. Wilson-plots for ammonia evaporation outside smooth tube A — runs R-717-129A to R-717-133A.

The variables for tube A are

$$r_o = 0.500 \text{ in. ,}$$

$$r_i = 0.435 \text{ in. ,}$$

$$k = 99 \text{ Btu}/\text{h} \cdot \text{ft} \cdot ^\circ\text{F} \text{ ,}$$

so that

$$\begin{aligned} R_{\text{wall}} &= \left(\frac{0.500 \text{ in.}}{99 \text{ Btu}/\text{h} \cdot \text{ft} \cdot ^\circ\text{F}} \right) \left(\frac{1 \text{ ft}}{12 \text{ in.}} \right) \times \ln \left(\frac{0.500 \text{ in.}}{0.435 \text{ in.}} \right) \\ &= 5.9 \times 10^{-5} (\text{Btu}/\text{h} \cdot \text{ft}^2 \cdot ^\circ\text{F})^{-1} . \end{aligned}$$

For the series of runs R-717-129A through R-717-133A, the average value of the composite heat transfer coefficient h_c^* obtained from the Wilson-plot is $1150 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$ (Fig. A.2). Thus, the evaporation-side heat transfer coefficient obtained from Eq. (A.6) is

$$h_e = \frac{1}{(1/1150 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}) - 5.9 \times 10^5 (\text{Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F})^{-1}}$$

$$= 1234 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} .$$

A.4 Nondimensional Quantities for Smooth Tube

The evaporation-side heat transfer coefficient h_e is usually considered equal to the evaporating film coefficient, since the dominant resistance lies in the evaporating film. Therefore, the evaporating film heat transfer coefficient can be put into the standard nondimensional form (using the normalizing factor ϕ) given by Eq. (6.2):

$$h_e/\phi = h_e/(k^3\rho^2g/\mu^2)^{1/3} , \quad (6.2)$$

where all fluid properties are evaluated at the average saturation temperature of ammonia at the evaporator module outlet $T_{N,o}$. The average ammonia temperature for runs R-717-129A through R-717-133A was 86.2719°F (Table A.3). Property values for ammonia at this temperature, taken from ASHRAE handbooks,^{15,20} are

$$k = 0.271 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F} ,$$

$$\rho = 37.14 \text{ lbm/ft}^3 ,$$

$$\mu = 0.325 \text{ lbm/ft}\cdot\text{h} ,$$

$$g = 4.17 \times 10^8 \text{ ft/h}^2 .$$

Thus, for $h_e = 1234 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}$, the nondimensional heat transfer coefficient from Eq. (6.2) is:

$$\begin{aligned} h_e/\phi &= (1234 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F}) / [(0.271 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F})^3 (37.14 \text{ lbm/ft}^3)^2 \\ &\quad \times (4.17 \times 10^8 \text{ ft/h}^2) / (0.325 \text{ lbm/h}\cdot\text{ft})^2]^{1/3} \\ &= 0.259 . \end{aligned}$$

The average liquid film Reynolds number is given by Eq. (6.1):

$$\overline{Re} = 4\overline{\Gamma}/\mu , \quad (6.1)$$

where $\overline{\Gamma}$ is the average mass flow of ammonia film per unit length of perimeter on the tube. The volume feed rate of ammonia at the top of tube A for the series of runs R-717-128A through R-717-132A is 0.0520 gpm. The perimeter of tube A is 3.14 in. (Table 3.1). Using Eq. (A.8),

$$\Gamma_{N,i} = \frac{(F_N)(\rho)}{P_t} . \quad (A.7)$$

The mass flow of ammonia at the top of the tube is

$$\begin{aligned} \Gamma_{N,i} &= \frac{(0.0520 \text{ gal/min})(0.1337 \text{ ft}^3/\text{gal})(60 \text{ min/h})(37.14 \text{ lbm/ft}^3)}{(3.14 \text{ in.})(1 \text{ ft}/12 \text{ in.})} \\ &= 59.21 \text{ lbm/h}\cdot\text{ft} . \end{aligned}$$

The average heat load Q for this series of runs is 5500 Btu/h. The mass flow of ammonia at the evaporator module outlet is given by Eq. (A.8)

$$\Gamma_{N,o} = \Gamma_{N,i} - \left(\frac{Q}{h_{fg}P_t} \right) , \quad (A.8)$$

where h_{fg} is the latent heat of ammonia at saturation conditions, or $h_{fg} = 492.4$ Btu/lbm. Thus, the outlet mass flow rate is

$$\begin{aligned}\Gamma_{N,o} &= 59.21 \text{ lbm/h}\cdot\text{ft} - \frac{(5500 \text{ Btu/h})(12 \text{ in./ft})}{(492.4 \text{ Btu/lbm})(3.14 \text{ in.})} \\ &= 16.52 \text{ lbm/h}\cdot\text{ft} .\end{aligned}$$

The average mass flow rate of ammonia $\bar{\Gamma}$ for this series of runs, given by Eq. (A.9), is

$$\begin{aligned}\bar{\Gamma} &= \frac{\Gamma_{N,i} + \Gamma_{N,o}}{2} = \frac{(59.21 \text{ lbm/h}\cdot\text{ft}) + (16.52 \text{ lbm/h}\cdot\text{ft})}{2} \quad (\text{A.9}) \\ &= 37.87 \text{ lbm/h}\cdot\text{ft} .\end{aligned}$$

The average liquid film Reynolds number for runs R-717-128A through R-717-132A, using Eq. (6.1), is

$$\begin{aligned}\overline{Re} &= \frac{(4)(37.87 \text{ lbm/h}\cdot\text{ft})}{(0.325 \text{ lbm/h}\cdot\text{ft})} \\ &= 4.66 \times 10^2 .\end{aligned}$$

Nondimensional heat transfer coefficients and average liquid film Reynolds numbers for this series of runs are presented in graphical form, along with results from other smooth tube tests (Fig. 6.1).

A.5 Water-Side Correlations

The water-side heat transfer coefficient can be estimated from Eqs. (5.15), (5.16), and (5.17). The correlation suggested by McAdams, Eq. (5.15), will be used to illustrate this method of determining the water-side coefficient for run R-717-129A. The mass flow rate of water G per

unit area is given by

$$G = \rho_w V_w , \quad (\text{A.10})$$

and for run R-717-129A, at an average bulk temperature of 93.3663°F,

$$\begin{aligned} G &= (62.08 \text{ lbm/ft}^3)(13.6 \text{ ft/s})(3600 \text{ s/h}) \\ &\cong 3.04 \times 10^6 \text{ lbm/h}\cdot\text{ft}^2 . \end{aligned}$$

Evaluating the properties of water at 93.3663°F,

$$k_b \cong 0.360 \text{ Btu/h}\cdot\text{ft}\cdot^\circ\text{F} ,$$

$$\mu_b \cong 1.706 \text{ lbm/ft}\cdot\text{h} ,$$

$$c_p \cong 0.998 \text{ Btu/lbm}\cdot^\circ\text{F} ;$$

for tube A,

$$D_h = \frac{0.87 \text{ in.}}{12 \text{ in./ft}} = 0.0725 \text{ ft} .$$

Using Eq. (5.15), the water-side heat transfer coefficient for run R-717-129A is

$$h_w \cong 0.023 \left(\frac{0.360}{0.0725} \right) \left[\frac{(3.04 \times 10^6)(0.0725)}{1.706} \right]^{0.8} \left[\frac{(1.706)(0.998)}{0.360} \right]^{0.4}$$

or

$$h_w \cong 2568 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} \text{ (Ref. 17).}$$

Similar calculations with Eqs. (5.16) and (5.17) yield

$$h_w \cong 2355 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F} \text{ (Ref. 18),}$$

and

$$h_w \approx 2800 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F (Ref. 19).}$$

Equation (5.8) can be used to calculate the composite evaporation heat transfer coefficient:

$$h_c^* = \frac{1}{(1/U_o) - (A_{t,o}/h_w A_i)} . \quad (5.8)$$

For tube A, the ratio $A_{t,o}/A_i$ can be calculated from values given in Table 3.1 and is found to be 1.15. Thus, for run R-717-128A,

$$\begin{aligned} h_c^* &= \frac{1}{(1/747) - (1.15/2568)} \\ &= 1122 \text{ Btu/h}\cdot\text{ft}^2\cdot^\circ\text{F (Ref. 17).} \end{aligned}$$

This value compares with 1150 Btu/h $\cdot$ ft² $\cdot$ °F obtained from Wilson-plot evaluation of the series of runs R-717-129A through R-717-133A. In principle, the composite heat transfer coefficient h_c^* can be calculated for each evaporation test run from the overall coefficient, water velocity, and water properties; therefore, one could evaluate a composite coefficient for each water velocity used in the Wilson-plot. However, the composite heat transfer coefficient in Eq. (5.8) is very sensitive to the water-side coefficient, especially at low water velocities (low water-side coefficients).

For evaporation tests with tube F, a 1/2-in.-diam rod was inserted through the tube center. This procedure effectively reduced the water cross-sectional flow area $A_{i,cs}$ from 0.004419 ft² to 0.003054 ft², and therefore increased the water velocity V_w by 44% for a given volume flow

rate F_w . Thus, accurate water-side coefficients were more easily determined using Eqs. (5.15), (5.16), and (5.17), but at the expense of accurate determination of overall coefficients from Eq. (5.1). This inaccuracy is due to the critical measurement of very small mean temperature differences ΔT [Eq. (5.2)].

Determination of accurate water-side coefficients for tests with doubly fluted tube H proved to be much more difficult due to the complicated geometry of the tube inside surface. Water-side correlations are applicable to tubes with smooth surfaces, but do not account for coefficient enhancement due to fluted surfaces. Thus, composite heat transfer coefficients obtained from Eq. (5.8), using the correlations given in Eqs. (5.15), (5.16), and (5.17), provided only a double check of results obtained from the Wilson-plot method.

Appendix B

WILSON-PLOT RESULTS

Tables B-1 through B-9 summarize the smoothed or average Wilson-plot results from thin film ammonia evaporation experiments performed on single, vertical tubes. Each table is classified according to ammonia feed rate at the top of the tube and the tube designation. The evaporator heat load, composite heat transfer coefficient, and composite temperature difference are averages for given conditions. Individual runs are documented in detail in Appendixes C and D.

Table B.1. Average Wilson-plot results for tube A

[Ammonia feed rate, $F_{N,i} \sim 3.155 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
1030 (3500)	5780 (1020)	1.7 (3.1)
1230 (4200)	6290 (1110)	2.0 (3.6)
1350 (4600)	6070 (1070)	2.3 (4.2)
1610 (5500)	6520 (1150)	2.5 (4.5)
1850 (6300)	6750 (1190)	2.8 (5.0)
2050 (7000)	6860 (1210)	3.1 (5.6)

Table B.2. Average Wilson-plot results for tube A

[Ammonia feed rate, $F_{N,i} \sim 6.309 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
880 (3,000)	5,900 (1,040)	1.6 (2.8)
1,050 (3,600)	6,460 (1,140)	1.7 (3.0)
1,260 (4,300)	6,800 (1,200)	1.9 (3.4)
1,550 (5,300)	7,600 (1,340)	2.1 (3.8)
1,790 (6,100)	8,050 (1,420)	2.3 (4.2)
2,140 (7,300)	8,900 (1,570)	2.5 (4.5)
2,400 (8,200)	9,580 (1,690)	2.6 (4.6)
2,580 (8,800)	9,870 (1,740)	2.7 (4.8)
2,810 (9,600)	10,490 (1,850)	2.8 (5.0)
3,020 (10,300)	10,720 (1,890)	2.9 (5.2)
3,190 (10,900)	10,830 (1,910)	3.1 (5.5)

Table B.3. Average Wilson-plot results for tube A

[Ammonia feed rate, $F_{N,i} \sim 15.773 \times 10^{-6} \text{ m}^3/\text{s}$ (0.250 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
910 (3,100)	6,350 (1,120)	1.4 (2.6)
1,050 (3,600)	6,460 (1,140)	1.6 (2.8)
1,290 (4,400)	7,540 (1,330)	1.7 (3.1)
1,440 (4,900)	8,220 (1,450)	1.8 (3.3)
1,580 (5,400)	8,560 (1,510)	1.9 (3.5)
1,850 (6,300)	8,960 (1,580)	2.1 (3.8)
2,140 (7,300)	9,700 (1,710)	2.3 (4.1)
2,400 (8,200)	10,660 (1,880)	2.3 (4.2)
2,670 (9,100)	11,060 (1,950)	2.5 (4.5)
2,990 (10,200)	11,340 (2,000)	2.7 (4.9)
3,220 (11,000)	11,510 (2,030)	2.8 (5.1)
3,460 (11,800)	12,190 (2,150)	2.9 (5.3)

Table B.4. Average Wilson-plot results for tube F

[Ammonia feed rate, $F_{N,i} \sim 3.155 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
880 (3000)	4540 (800)	2.0 (3.6)
1260 (4300)	4310 (760)	3.0 (5.4)
1580 (5400)	4140 (730)	3.9 (7.1)
1760 (6000)	3740 (660)	4.9 (8.8)
1880 (6400)	3630 (640)	5.3 (9.5)
2050 (7000)	3630 (640)	5.9 (10.6)

Table B.5. Average Wilson-plot results for tube F

[Ammonia feed rate, $F_{N,i} \sim 6.309 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
880 (3,000)	5,270 (930)	1.7 (3.1)
1,170 (4,000)	5,840 (1,030)	2.1 (3.7)
1,470 (5,000)	6,290 (1,110)	2.4 (4.3)
1,760 (6,000)	6,800 (1,200)	2.7 (4.8)
2,020 (6,900)	6,920 (1,220)	3.1 (5.5)
2,580 (8,800)	6,630 (1,170)	4.0 (7.2)
2,930 (10,000)	6,460 (1,140)	4.7 (8.5)

Table B.6. Average Wilson-plot results for tube F

[Ammonia feed rate, $F_{N,i} \sim 15.773 \times 10^{-6} \text{ m}^3/\text{s}$ (0.250 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
970 (3,300)	7,600 (1,340)	1.3 (2.4)
1,110 (3,800)	7,940 (1,400)	1.4 (2.6)
1,320 (4,500)	8,280 (1,460)	1.7 (3.0)
1,700 (5,800)	8,730 (1,540)	2.0 (3.6)
1,880 (6,400)	9,070 (1,600)	2.2 (3.9)
2,490 (8,500)	9,750 (1,720)	2.7 (4.8)
2,900 (9,900)	10,150 (1,790)	3.0 (5.4)
3,140 (10,700)	10,660 (1,880)	3.1 (5.6)
3,310 (11,300)	10,660 (1,880)	3.3 (5.9)

Table B.7. Average Wilson-plot results for tube H

[Ammonia feed rate, $F_{N,i} \sim 3.155 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
820 (2800)	3060 (540)	1.7 (3.0)
1030 (3500)	2610 (460)	2.4 (4.4)
1290 (4400)	2780 (490)	2.9 (5.2)
1550 (5300)	2840 (500)	3.4 (6.1)
1850 (6300)	3060 (540)	3.7 (6.6)
2050 (7000)	3350 (590)	3.9 (7.0)

Table B.8. Average Wilson-plot results for tube H

[Ammonia feed rate, $F_{N,i} \sim 6.309 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
910 (3,100)	4,650 (820)	1.2 (2.2)
1,030 (3,500)	5,330 (940)	1.2 (2.2)
1,200 (4,100)	5,330 (940)	1.4 (2.5)
1,440 (4,900)	5,500 (970)	1.6 (2.9)
1,760 (6,000)	6,120 (1,080)	1.8 (3.2)
2,080 (7,100)	6,350 (1,120)	2.0 (3.6)
2,400 (8,200)	6,070 (1,070)	2.4 (4.4)
2,670 (9,100)	6,580 (1,160)	2.5 (4.5)
2,930 (10,000)	6,240 (1,100)	2.9 (5.2)
3,220 (11,000)	6,350 (1,120)	3.1 (5.6)
3,460 (11,800)	6,290 (1,110)	3.4 (6.1)
3,630 (12,400)	6,240 (1,100)	3.6 (6.5)

Table B.9. Average Wilson-plot results for tube H

[Ammonia feed rate, $F_{N,i} \sim 15.773 \times 10^{-6} \text{ m}^3/\text{s}$ (0.250 gpm)]

Q, heat load [W (Btu/h)]	h_c^* , composite heat transfer coefficient [W/m ² ·K (Btu/h·ft ² ·°F)]	ΔT_c^* , composite temperature difference [K (°F)]
1,030 (3,500)	3,630 (640)	1.7 (3.1)
1,290 (4,400)	4,710 (830)	1.7 (3.1)
1,760 (6,000)	5,100 (900)	2.2 (3.9)
1,990 (6,800)	5,330 (940)	2.4 (4.3)
2,340 (8,000)	5,330 (940)	2.7 (4.9)
2,490 (8,500)	5,560 (980)	2.8 (5.0)
2,780 (9,500)	5,100 (900)	3.4 (6.1)
3,080 (10,500)	5,270 (930)	3.6 (6.5)
3,370 (11,500)	5,950 (1,050)	3.5 (6.3)
3,570 (12,200)	6,800 (1,200)	3.3 (6.0)

Appendix C

EXPERIMENTAL DATA

Tables C.1 through C.9 document 563 runs which yielded 79 heat transfer data points. The tables summarize experimental data used in data reduction and for construction of Wilson-plots. In addition, the tables present composite evaporation heat transfer coefficients calculated by backing out water-side coefficients, a method suggested by McAdams and illustrated in Appendix A. The tables are presented in the following order:

<u>Table</u>	<u>Tube</u>	<u>Ammonia feedrate</u>
C.1	Smooth tube A	$\sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm)
C.2	Smooth tube A	$\sim 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm)
C.3	Smooth tube A	$\sim 15.77 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm)
C.4	Externally fluted tube F	$\sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm)
C.5	Externally fluted tube F	$\sim 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm)
C.6	Externally fluted tube F	$\sim 15.77 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm)
C.7	Doubly fluted tube H	$\sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.05 gpm)
C.8	Doubly fluted tube H	$\sim 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.10 gpm)
C.9	Doubly fluted tube H	$\sim 15.77 \times 10^{-6} \text{ m}^3/\text{s}$ (0.25 gpm)

Table C. 1. Experimental data for smooth tube A, $P_{w,1} \sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpa)

ROW NUMBER	P H ₂ I	T H ₂ O	F W	V W	P GPM	DEG F	T W, AVG	DT W	Q	RP	DT W	FPS	BTU/HR	U	H	W	H ⁴ C	DT ⁴ C
---BTU/HR FT ² P--- DEG F																		
P-717-100A	0.0506	84.8482	84.7	45.7	88.0975	0.0649	2737.	2.7	3.2493	0.0470	805.	6603.	936.	2.79				
P-717-101A	0.0519	82.3749	8.9	4.8	88.8667	0.7054	3128.	2.5	6.4918	0.2848	460.	1094.	891.	3.35				
P-717-102A	0.0518	80.4778	84.9	45.8	84.2793	0.0759	3211.	2.4	3.8015	0.0469	807.	6485.	941.	3.26				
P-717-103A	0.0519	85.0982	25.6	13.8	89.6534	0.2528	3222.	2.4	4.5551	0.1224	676.	2557.	970.	3.17				
P-717-104A	0.0519	82.3789	11.6	6.3	88.4328	0.5700	3299.	2.3	6.0539	0.2301	520.	1351.	934.	3.37				
P-717-105A	0.0519	82.4764	13.5	7.3	88.2656	0.4936	3329.	2.3	5.7891	0.2036	549.	1526.	937.	3.39				
P-717-106A	0.0519	82.3776	18.1	9.8	87.6409	0.3686	3329.	2.3	5.2633	0.1612	604.	1921.	946.	3.36				
P-717-107A	0.0519	84.9246	39.8	21.5	89.1642	0.1694	3360.	2.3	4.2396	0.0859	757.	3634.	995.	3.22				
P-717-108A	0.0519	81.9183	85.7	46.3	85.8794	0.0791	3373.	2.3	3.5601	0.0465	813.	6588.	948.	3.40				
P-717-109A	0.0519	84.0712	7.5	4.1	91.7410	0.9031	3393.	2.3	7.6698	0.3251	423.	973.	844.	3.84				
P-717-110A	0.0519	82.3543	26.3	14.2	87.1707	0.2646	3470.	2.2	4.8164	0.1196	688.	2582.	992.	3.34				
P-717-111A	0.0518	81.9733	40.7	22.0	86.3144	0.1762	3572.	2.2	4.3411	0.0844	786.	3643.	1045.	3.26				
P-717-112A	0.0520	85.8884	13.9	7.5	92.1114	0.5192	3586.	2.1	6.2231	0.1997	550.	1587.	915.	3.74				
P-717-113A	0.0507	85.7965	18.7	10.1	91.4626	0.3936	3665.	2.0	5.6661	0.1573	618.	2008.	956.	3.66				
P-717-114A	0.0519	82.5516	84.5	45.6	86.5719	0.0881	3707.	2.1	4.0203	0.0471	881.	6540.	1042.	3.40				
P-717-115A	0.0519	84.1327	11.5	6.2	91.2207	0.7116	4068.	1.9	7.0879	0.2324	548.	1358.	1023.	3.80				
P-717-116A	0.0519	82.6680	40.9	22.1	87.3816	0.2023	4123.	1.9	4.7136	0.0841	835.	3677.	1131.	3.48				
P-717-117A	0.0519	81.8216	18.4	9.9	89.9146	0.4551	4163.	1.8	6.0970	0.1595	652.	1964.	1055.	3.77				
P-717-118A	0.0519	83.4160	26.0	14.0	88.8681	0.3287	4257.	1.8	5.4521	0.1208	746.	2580.	1117.	3.64				
P-717-119A	0.0519	84.1674	14.0	7.6	90.9449	0.6176	4310.	1.8	6.8273	0.1981	603.	1591.	1068.	3.85				
P-717-120A	0.0519	83.8049	10.8	5.8	92.1139	0.8474	4568.	1.7	8.3289	0.2435	524.	1302.	975.	4.48				
P-717-121A	0.0519	84.1956	8.8	4.7	93.2821	1.0490	4578.	1.7	9.0866	0.2884	481.	1106.	963.	4.54				
P-717-122A	0.0519	83.5377	14.1	7.6	91.2363	0.6660	4663.	1.6	7.6985	0.1976	579.	1597.	991.	4.49				
P-717-123A	0.0519	81.2068	19.1	10.3	90.0803	0.4899	4664.	1.6	6.8735	0.1545	648.	2030.	1024.	4.35				
P-717-124A	0.0519	82.4531	40.7	22.0	88.1276	0.2317	4693.	1.6	5.6744	0.0845	790.	3675.	1049.	4.27				
P-717-125A	0.0544	82.8544	25.8	13.9	89.1177	0.3655	4700.	1.7	6.2633	0.1215	717.	2568.	1055.	4.25				

Table C.1 (continued)

Run number	F	T	P	V	T	u_{AV}	ΔT	Q	RP	ΔT	Y	U	H	H*	ΔT^*
	u_c	u_c	W	W	W	W	W	BTU/HR			FPS	O	W	C	C
	GRY	DEG F	GPM	PFS	DEG F	DEG F	DEG F						---RTD/HR	FT ² /F	DEG F
R-717-126A	0.0520	85.7895	85.7	46.3	91.2446	0.1135	5058.	1.5	5.4551	0.0465		896.	6782.	1042.	4.64
R-717-127A	0.0520	97.4261	8.0	4.3	97.9173	1.2898	5117.	1.5	10.4912	0.3113		466.	1049.	954.	5.12
R-717-128A	0.0520	96.7633	18.9	10.2	94.2105	0.5478	5165.	1.5	7.4472	0.1557		662.	2057.	1052.	4.69
R-717-129A	0.0520	86.5365	25.1	13.6	93.3663	0.4270	5341.	1.4	6.8297	0.1242		747.	2568.	1122.	4.55
R-717-130A	0.0519	94.2156	84.8	45.8	89.9636	0.1301	5491.	1.4	5.6481	0.0469		929.	6678.	1105.	4.75
R-717-131A	0.0520	87.2107	11.7	6.3	96.8050	0.9622	5591.	1.4	9.5944	0.2294		557.	1415.	1016.	5.26
R-717-132A	0.0520	86.4060	41.2	22.2	92.6898	0.2714	5603.	1.4	6.2037	0.0837		852.	3799.	1147.	4.66
R-717-133A	0.0520	86.8907	14.1	7.6	96.1963	0.8131	5728.	1.3	9.3061	0.1976		588.	1638.	1001.	5.47
R-717-134A	0.0520	84.8662	25.5	13.8	92.9209	0.4690	5865.	1.3	8.0347	0.1226		707.	2597.	1030.	5.53
R-717-135A	0.0520	85.3294	18.8	10.2	93.8631	0.6638	6228.	1.2	8.5337	0.1563		697.	2046.	1146.	5.19
R-717-136A	0.0519	84.7927	41.2	22.2	91.5911	0.3042	6240.	1.2	6.7975	0.0836		877.	3781.	1195.	4.99
R-717-137A	0.0520	85.3654	11.0	5.9	96.4497	1.1503	6709.	1.2	11.0843	0.2402		544.	1349.	1013.	5.95
R-717-138A	0.0520	95.4761	8.9	4.8	97.3431	1.4315	6314.	1.2	11.8670	0.2860		508.	1138.	1044.	5.78
R-717-139A	0.0520	95.3112	13.4	7.5	95.3413	0.9266	6401.	1.2	10.0325	0.1997		609.	1613.	1377.	5.68
R-717-140A	0.0520	96.1371	14.4	7.8	97.2141	0.9146	6696.	1.1	11.0771	0.1940		577.	1677.	956.	6.69
R-717-141A	0.0520	84.8394	85.6	46.2	92.5091	0.1534	6752.	1.1	7.6698	0.0466		941.	6820.	980.	6.58
R-717-142A	0.0520	95.9362	11.8	6.4	97.9259	1.1771	6995.	1.1	11.8896	0.2279		554.	1431.	998.	6.60
R-717-143A	0.0520	86.6101	46.5	21.8	94.6791	0.3437	6922.	1.1	8.6690	0.0949		819.	3773.	1092.	6.05
R-717-144A	0.0520	85.6647	25.9	14.0	95.3113	0.5402	6058.	1.1	9.6537	0.1213		688.	2656.	981.	6.78
R-717-145A	0.0520	86.2856	19.2	10.4	95.7716	0.7181	7063.	1.1	9.4860	0.1539		711.	2098.	1165.	5.79

Table C.2. Experimental data for smooth tube A, $F_{N,1} = 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)

RUN NUMBER	F N ₁	T N ₂ O	P W	V W	T W, AVG	ΔT W	Q BTU/HR	RP	ΔT	Y	O	H W	H [*] C	ΔT^* C
	GPM	DEG F	GPM	FPS	DEG F	DEG F	BTU/HR		DEG F	FPS	---	BTU/HR	FT ² P	DEG F
R-717-146A	0.1003	71.9026	93.4	50.4	75.6799	0.0592	2705.	5.7	3.8773	0.0434	666.	6661.	753.	3.43
R-717-147A	0.1005	75.9150	92.3	49.8	79.6340	0.0694	3140.	4.9	3.7191	0.0439	807.	6749.	916.	3.21
R-717-148A	0.1005	76.1156	66.1	35.7	86.0210	0.1031	3391.	4.5	3.8954	0.0573	834.	5180.	1023.	3.17
R-717-149A	0.1003	72.5154	66.2	35.8	76.9881	0.1034	3411.	4.5	4.3728	0.0572	745.	5095.	895.	3.64
R-717-150A	0.1003	73.1473	64.3	34.7	76.6510	0.1071	3427.	4.5	3.5038	0.0586	934.	4967.	1192.	2.75
R-717-151A	0.1003	73.3675	9.9	5.4	79.6554	0.1158	3542.	4.3	6.2879	0.2609	538.	1135.	1181.	2.86
R-717-152A	0.1003	73.6711	94.5	51.0	77.2672	0.0758	3576.	4.3	3.5960	0.0430	948.	6789.	1130.	3.02
R-717-153A	0.1003	73.3907	47.5	25.6	79.3972	0.1549	3661.	4.2	5.0065	0.0746	698.	3939.	877.	3.99
R-717-154A	0.1005	76.1191	45.0	24.3	80.4624	0.1837	3668.	4.2	4.3233	0.0779	810.	3818.	1072.	3.27
R-717-155A	0.1003	73.1662	20.3	15.3	77.6161	0.2641	3722.	4.1	4.4499	0.1129	799.	2593.	1217.	2.87
R-717-156A	0.1003	73.2944	47.3	25.6	77.2335	0.1507	3764.	4.1	3.9551	0.0748	909.	3903.	1241.	2.90
R-717-157A	0.1004	73.8192	19.4	9.9	80.1309	0.4122	3780.	4.1	6.3716	0.1592	567.	1866.	870.	4.15
R-717-158A	0.1006	76.6292	10.5	5.6	83.6945	0.7443	3874.	3.9	7.0625	0.2505	524.	1209.	1043.	3.55
R-717-159A	0.1003	73.5151	20.0	10.8	79.6539	0.3301	3875.	4.0	5.1337	0.1493	721.	1973.	1243.	2.93
R-717-160A	0.1003	72.2772	94.1	50.8	76.7945	0.0333	3903.	4.0	4.5173	0.0432	825.	6743.	960.	3.83
R-717-161A	0.1004	73.8487	29.7	15.5	79.7459	0.2766	3956.	3.9	5.8972	0.1116	641.	2656.	887.	4.26
R-717-162A	0.1004	74.1378	94.5	51.0	79.7004	0.0950	3997.	3.8	4.5626	0.0430	837.	6843.	974.	3.92
R-717-163A	0.1004	74.0627	10.3	5.4	82.3097	0.8072	4050.	3.8	8.3371	0.2579	464.	1166.	855.	4.52
R-717-164A	0.1006	76.5465	23.3	15.5	83.6437	0.2351	4086.	3.7	5.1023	0.1114	765.	2689.	1136.	3.43
R-717-165A	0.1003	73.6702	9.5	5.1	81.4919	0.8670	4107.	3.7	7.8236	0.2701	501.	1103.	1045.	3.75
R-717-166A	0.1003	73.8280	10.3	5.5	79.2377	0.8062	4120.	3.7	7.4036	0.2502	531.	1162.	1119.	3.52
R-717-167A	0.1004	73.7337	66.1	35.7	79.1577	0.1255	4133.	3.7	4.4400	0.0573	888.	5127.	1109.	3.56
R-717-168A	0.1004	73.7980	19.1	10.3	79.9692	0.4351	4143.	3.7	6.0911	0.1545	651.	1919.	1066.	3.71
R-717-169A	0.1005	76.8334	18.0	9.7	82.9667	0.4662	4167.	3.7	6.0332	0.1625	660.	1856.	1115.	3.57
R-717-170A	0.1003	73.3961	46.7	25.2	76.0116	0.1822	4240.	3.6	4.6175	0.0756	877.	3835.	1190.	3.40
R-717-171A	0.1004	73.7508	27.0	15.0	79.2625	0.3071	4250.	3.6	5.5417	0.1146	732.	2579.	1087.	3.73

Table C.2 (continued)

END NUMBER	F	N, I	T	H ₂ O	P	V	W	T	W, AVG	ΔT	Q	RP	ΔT	Y	U	H	H*	AT*
	GPM	DEG F	GPM	FPS	DEG F	DEG F	W, AVG	DEG F	DEG F	BTU/HR	DEG F	FPS	DEG F	DEG F	---	BTU/HR	FT ² /P	DEG F
R-77-77A	0.1006	77.2636	9.0	4.9	84.8222	0.9439	4251.	3.6	7.5586	0.2812	537.	1084.	1248.	3.25				
R-77-77A	0.1002	77.9357	18.9	10.2	78.0002	0.4529	4270.	3.6	6.0645	0.1557	673.	1884.	1141.	3.58				
R-77-77A	0.1004	77.7115	48.1	26.0	78.6319	0.1795	4297.	3.6	4.9203	0.0739	834.	3985.	1098.	3.74				
R-77-77A	0.1006	77.7233	94.5	51.0	81.6237	0.0919	4325.	3.5	3.9004	0.0420	1059.	6561.	1284.	3.22				
R-77-77A	0.1002	77.9190	28.3	15.3	77.2037	0.3078	4339.	3.6	5.2846	0.1129	784.	2586.	1204.	3.44				
R-77-77A	0.1002	77.4576	75.1	40.6	75.6869	0.1197	4480.	3.5	4.2293	0.0517	1012.	5596.	1277.	3.35				
R-77-77A	0.1007	77.2160	19.0	10.3	84.9133	0.5550	5259.	2.9	6.6442	0.1551	756.	1967.	1354.	3.71				
R-77-77A	0.1006	77.2903	94.3	50.9	81.3128	0.1134	5324.	2.9	4.0324	0.0431	1261.	6935.	1594.	3.19				
R-77-77A	0.1007	77.6023	27.6	14.9	95.0426	0.4243	5822.	2.6	6.3503	0.1153	976.	2647.	1413.	3.94				
R-77-77A	0.1003	80.2726	46.9	25.2	85.5502	0.2493	5824.	2.6	5.2776	0.0754	1054.	4062.	1502.	3.70				
R-77-77A	0.1006	77.7985	19.0	10.2	85.2061	0.6263	5920.	2.6	7.4076	0.1554	763.	1566.	1378.	4.10				
R-77-77A	0.1007	79.1729	8.6	4.7	88.6435	1.4281	6132.	2.5	10.4706	0.2922	559.	1065.	1411.	4.15				
R-77-77A	0.1007	79.0771	29.5	15.9	84.6849	0.4132	6149.	2.5	6.6073	0.1091	889.	2791.	1402.	4.19				
R-77-77A	0.1006	77.8037	94.4	50.9	83.1207	0.1317	6189.	2.5	5.3169	0.0431	1112.	7009.	1360.	4.35				
R-77-77A	0.1003	79.3788	9.2	5.0	89.4933	1.3589	6216.	2.4	9.6122	0.2778	618.	1126.	1673.	3.55				
R-77-77A	0.1007	77.4001	47.0	25.8	84.3954	0.2735	6503.	2.3	5.9954	0.0743	1038.	4094.	1464.	4.24				
R-77-77A	0.1007	79.5096	65.7	35.5	84.4050	0.2073	6792.	2.2	5.8054	0.0576	1116.	5285.	1473.	4.40				
R-77-77A	0.1006	77.8072	66.4	35.9	83.6911	0.2102	6950.	2.2	4.8839	0.0571	1359.	5280.	1910.	3.44				
R-77-77A	0.1007	77.4439	94.4	50.9	83.5004	0.1502	7051.	2.2	5.0515	0.0431	1334.	7024.	1707.	3.95				
R-77-77A	0.1003	77.1890	94.4	50.9	80.3605	0.1521	7144.	2.2	7.1714	0.0431	951.	6900.	1131.	6.03				
R-77-77A	0.1006	77.3058	94.4	50.9	82.6933	0.1534	7207.	2.1	5.3975	0.0431	1278.	6992.	1617.	4.26				
R-77-77A	0.1007	79.0197	24.1	15.2	85.8339	0.5209	7282.	2.1	6.8131	0.1136	1021.	2698.	1807.	3.85				
R-77-77A	0.1009	80.5275	65.5	35.3	86.2962	0.2244	7317.	2.1	5.7687	0.0577	1241.	5325.	1640.	4.26				
R-77-77A	0.1007	79.0171	46.0	24.8	84.8673	0.3199	7332.	2.1	5.8509	0.0765	1197.	3985.	1828.	3.83				
R-77-77A	0.1007	79.6567	49.4	26.1	85.1239	0.3130	7665.	2.0	6.4672	0.0735	1132.	4156.	1648.	4.44				
R-77-77A	0.1004	77.8671	27.5	14.9	83.2617	0.5717	7832.	2.0	9.3946	0.1155	796.	2617.	1224.	6.11				

Table C.2 (continued)

FW NUMBER	F	T	P	V	T	ΔT	Q	RF	ΔT	Y	U	H	H*	ΔT*
	N, I	H ₂ O	GPM	FPS	W, AVG	DEG F	BTU/HR			FPS			C	C
		DEG F												
R-717-193A	0.1003	80.5705	18.8	10.1	89.3941	0.8462	7899.	1.9	8.8235	0.1570	855.	1991.	1689.	4.47
R-717-193A	0.1003	73.3758	66.8	36.1	80.9579	0.2377	7909.	1.9	7.5821	0.0568	996.	5255.	1274.	5.93
R-717-200A	0.1003	80.5799	18.5	10.0	89.5485	0.8878	8163.	1.8	8.9688	0.1589	869.	1968.	1766.	4.42
R-717-200A	0.1007	79.3844	28.7	15.5	87.2788	0.5924	8462.	1.8	7.8943	0.1117	1024.	2766.	1702.	4.54
R-717-200A	0.1004	74.1980	18.9	10.2	85.6014	0.9132	8588.	1.8	11.4034	0.1560	719.	1962.	1243.	6.60
R-717-200A	0.1007	79.2370	93.8	50.6	86.7057	0.1833	8562.	1.8	8.4687	0.0433	966.	7114.	1144.	7.15
R-717-200A	0.1010	92.3491	27.4	14.8	90.5019	0.6346	8649.	1.7	8.1538	0.1160	1013.	2710.	1776.	4.65
R-717-200A	0.1004	74.2499	47.4	25.6	82.9950	0.3713	9768.	1.8	0.7451	0.0747	958.	4040.	1316.	6.36
R-717-200A	0.1010	83.3558	9.9	5.4	95.9033	1.7787	9800.	1.7	12.5525	0.2609	670.	1239.	1768.	4.75
R-717-207A	0.1010	83.6559	18.5	10.0	93.4335	0.9531	8832.	1.7	9.7776	0.1586	863.	2013.	1701.	4.96
R-717-200A	0.1011	84.9324	0.8	5.3	99.0007	1.8974	9211.	1.6	14.0783	0.2649	625.	1239.	1487.	5.92
R-717-200A	0.1006	77.1068	94.6	51.1	83.7341	0.1960	9236.	1.6	6.6274	0.0430	1331.	7050.	1700.	5.19
R-717-200A	0.1010	92.6997	45.1	24.3	89.9393	0.4117	9244.	1.6	7.3072	0.0778	1208.	4030.	1943.	4.79
R-717-200A	0.1007	79.5372	65.8	35.5	87.7674	0.2333	9473.	1.6	9.2303	0.0575	990.	5386.	1240.	7.30
R-717-200A	0.1003	79.3577	65.6	35.4	86.7653	0.2942	9611.	1.6	6.9075	0.0576	1329.	5348.	1860.	4.93
R-717-200A	0.1007	79.4330	29.0	15.6	87.5150	0.6702	9666.	1.6	9.0820	0.1108	1017.	2791.	1749.	5.28
R-717-200A	0.1010	82.6953	64.9	35.0	89.4165	0.3618	9749.	1.5	6.7212	0.0582	1385.	5374.	1969.	4.73
R-717-200A	0.1004	90.3389	9.7	5.2	94.6611	2.0334	9823.	1.5	14.3222	0.2659	655.	1208.	1740.	5.39
R-717-200A	0.1007	79.1175	45.7	24.7	86.1924	0.4386	9980.	1.5	8.0749	0.0770	1180.	3991.	1788.	5.33
R-717-200A	0.1012	95.4533	19.9	10.7	96.7903	1.0259	10151.	1.5	11.3370	0.1498	955.	2166.	1566.	6.19
R-717-200A	0.1007	79.2702	93.5	50.5	86.8543	0.2223	10343.	1.5	7.5941	0.0434	1303.	7166.	1651.	5.98
R-717-200A	0.1006	77.8657	66.2	35.8	85.2245	0.3172	10458.	1.5	7.3589	0.0572	1357.	5342.	1917.	5.21
R-717-200A	0.1009	90.1131	46.2	24.9	89.0763	0.4687	10773.	1.4	8.9637	0.0763	1148.	4087.	1695.	6.07
R-717-200A	0.1009	81.302	29.5	15.9	91.8123	0.7425	10899.	1.4	10.4926	0.1093	992.	2896.	1636.	6.36
R-717-200A	0.1009	79.5027	65.7	35.5	87.9147	0.3391	11063.	1.4	8.3120	0.0576	1271.	5304.	1745.	6.06
R-717-200A	0.1009	81.5044	18.3	9.9	93.6125	1.2160	11095.	1.4	12.1082	0.1599	875.	1998.	1763.	6.01

Table C.3 (continued)

FIR NUMBER	F N, I	T W, O	P W	V W	T W, AVG	ΔT V	Q	RF	$\frac{\Delta T}{\Delta T}$	Y	U	H O	H [*] C	ΔT^* C
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR		DEG F	PPS		---BTU/HR FT ² °F---		DEG F
F-717-250A	0.2460	68.6583	76.5	41.3	73.0519	0.1422	5418.	7.1	4.3956	0.0509	1177.	5590.	1553.	3.33
F-717-251A	0.2469	73.8592	29.3	15.8	79.5739	0.3754	5467.	6.9	5.7146	0.1100	914.	2691.	1499.	3.48
F-717-252A	0.2474	76.0556	29.0	15.6	81.4773	0.3793	5470.	6.9	5.4213	0.1108	964.	2700.	1634.	3.20
F-717-253A	0.2459	68.1129	64.9	35.0	72.7720	0.1803	5829.	6.6	4.6591	0.0581	1195.	4892.	1661.	3.35
F-717-254A	0.2474	76.5728	42.1	22.7	81.8632	0.2918	6115.	6.1	5.2954	0.0822	1103.	3649.	1690.	3.46
F-717-255A	0.2470	74.5052	44.4	24.0	80.0063	0.2797	6182.	6.1	5.5011	0.0708	1073.	3767.	1596.	3.70
F-717-256A	0.2470	74.7887	63.4	34.2	80.0399	0.1986	6267.	6.0	5.2512	0.0593	1140.	5009.	1544.	3.88
F-717-257A	0.2471	74.6827	18.5	10.0	81.8331	0.6834	6300.	6.0	7.1503	0.1586	841.	1891.	1722.	3.49
F-717-258A	0.2470	74.4283	92.3	49.8	79.0245	0.1373	6307.	6.0	4.5962	0.0439	1311.	6728.	1689.	3.57
F-717-259A	0.2473	75.0506	92.1	49.7	80.1845	0.1400	6410.	5.9	5.1339	0.0439	1194.	6762.	1498.	4.09
F-717-260A	0.2473	76.2186	94.3	50.9	81.0671	0.1424	6686.	5.6	4.8485	0.0431	1317.	6926.	1686.	3.79
F-717-261A	0.2483	81.6072	28.0	15.1	88.4462	0.5182	7232.	5.1	6.8790	0.1138	1004.	2733.	1738.	3.97
F-717-262A	0.2481	81.0798	43.0	23.2	87.0617	0.3398	7279.	5.1	5.9819	0.0908	1162.	3822.	1787.	3.89
F-717-263A	0.2483	82.0598	17.1	9.2	90.4000	0.8595	7322.	5.1	8.3401	0.1689	830.	1860.	1740.	4.02
F-717-264A	0.2484	82.6711	9.2	5.0	93.2219	1.6075	7390.	5.0	10.5508	0.2766	669.	1152.	2011.	3.51
F-717-265A	0.2473	75.8649	33.7	18.2	82.3632	0.4427	7420.	5.1	6.4953	0.0982	1092.	3063.	1851.	3.83
F-717-266A	0.2482	81.4020	65.6	35.4	86.9266	0.2432	7946.	4.7	5.5246	0.0576	1374.	5352.	1949.	3.89
F-717-267A	0.2485	83.5241	31.3	16.9	90.4756	0.5223	8131.	4.5	6.9515	0.1043	1117.	3014.	1946.	3.99
F-717-268A	0.2435	83.3580	10.8	10.1	91.9313	0.8730	8170.	4.5	8.5733	0.1567	910.	2021.	1887.	4.14
F-717-269A	0.2473	76.2714	45.3	24.5	82.6245	0.3639	8211.	4.6	6.3532	0.0775	1234.	3888.	1944.	4.03
F-717-270A	0.2483	82.1574	94.4	51.0	87.8356	0.1826	8582.	4.3	5.6782	0.0431	1444.	7195.	1876.	4.37
F-717-271A	0.2477	79.4950	65.8	35.5	84.3962	0.2689	8812.	4.2	5.9012	0.0575	1426.	5291.	2066.	4.07
F-717-272A	0.2473	76.1896	75.8	40.9	81.8772	0.2336	8819.	4.3	5.6876	0.0513	1481.	5844.	2090.	4.03
F-717-273A	0.2485	83.4293	9.5	5.1	95.4911	1.8794	8904.	4.1	12.0628	0.2701	705.	1194.	2194.	3.88
F-717-274A	0.2484	82.3371	92.8	50.1	87.8339	0.1955	9031.	4.1	5.4967	0.0437	1569.	7094.	2104.	4.10
F-717-275A	0.2495	83.3830	42.1	22.7	90.2040	0.4330	9085.	4.1	6.8210	0.0821	1272.	3821.	2061.	4.21

Table G.3 (continued)

SHIP NUMBER	F H ₂ I	T H ₂ O	P W	V W	T W, AVG	ΔT W	Q	RP	ΔT	FPS	Y	U O	H W	R* C	ΔT* C
	GPM	DEG F	GPM	FPS	DEG F	DEG F	BTU/HR					---BTU/HR	F* ²	F--- C	DEG F
R-717-276A	0.2477	79.5280	29.5	15.4	86.9931	0.6540	9205.	4.0	8.4652	0.1121		1049.	2751.	1867.	4.76
R-717-277A	0.2486	81.9117	66.0	35.6	90.3154	0.3005	9868.	3.7	6.4037	0.0574		1472.	5472.	2131.	4.42
R-717-279A	0.2479	79.7861	27.3	14.9	89.8196	0.7416	10090.	3.7	9.0125	0.1161		1067.	2683.	1965.	4.90
R-717-279A	0.2479	79.4411	42.5	22.9	87.2515	0.4919	10243.	3.6	7.8104	0.0815		1253.	3789.	2020.	4.84
R-717-280A	0.2481	80.5424	18.7	10.1	91.3466	1.1152	10384.	3.6	10.8062	0.1573		918.	2007.	1935.	5.12
R-717-281A	0.2491	80.7094	19.0	10.2	91.4468	1.1174	10561.	3.5	10.7374	0.1554		939.	2032.	2005.	5.03
R-717-282A	0.2483	82.1710	10.4	5.6	96.5925	2.0856	10757.	3.4	14.4215	0.2523		712.	1285.	1964.	5.23
R-717-282A	0.2482	81.3367	9.3	5.0	96.1922	2.3715	10958.	3.4	14.9555	0.2755		700.	1174.	2221.	4.71
R-717-284A	0.2481	80.9107	45.7	24.7	88.9162	0.4812	10904.	3.4	8.0055	0.0770		1312.	4050.	2089.	5.03
R-717-285A	0.2481	80.7243	94.3	50.9	87.8404	0.2370	11127.	3.3	7.1161	0.0431		1493.	7189.	1962.	5.42
R-717-286A	0.2480	80.2269	65.7	35.4	97.6413	0.3522	11515.	3.2	7.4164	0.0576		1483.	5376.	2171.	5.07
R-717-287A	0.2431	80.8030	94.5	51.0	88.0992	0.2494	11728.	3.2	7.2962	0.0431		1535.	7208.	2033.	5.51
R-717-288A	0.2491	80.6861	66.1	35.7	88.2627	0.3570	11756.	3.2	7.5766	0.0573		1482.	5425.	2160.	5.20
R-717-288A	0.2489	85.6823	14.5	7.8	99.0631	1.6571	11949.	3.1	13.3809	0.1930		853.	1701.	2014.	5.67

Table C.4. Experimental data for externally fluted tube F, $F_{N,1} \sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpm)

Run Number	F N ₁	T H ₂ O	P W	V W	T W, AVG	ΔT W	Q BTU/HR	RP	ΔT	Y	U O	H W	R [*] C	ΔT^* C
	GPM	DEG F	GPM	FPS	DEG F	DEG F	BTU/HR		DEG F	FPS			---	DEG F
R-77-100F	0.0517	78.6186	36.1	26.3	83.2727	0.1664	2990.	2.6	4.6547	0.0730	619.	4834.	721.	3.99
R-77-101F	0.0519	80.3214	62.5	45.6	86.6244	0.1123	3496.	2.2	6.3031	0.0471	534.	7843.	579.	5.81
R-77-102F	0.0519	79.6081	23.0	16.8	86.0690	0.3157	3610.	2.2	6.4608	0.1049	538.	3420.	652.	5.33
R-77-103F	0.0519	79.9584	16.8	12.3	87.1331	0.4420	3703.	2.1	7.1747	0.1345	497.	2682.	626.	5.76
R-77-104F	0.0519	81.7821	62.7	45.7	89.5333	0.1198	3729.	2.1	6.7509	0.0470	534.	7735.	578.	6.23
R-77-105F	0.0519	80.6616	13.2	9.6	89.0067	0.5715	3761.	2.1	7.9451	0.1632	456.	2221.	591.	6.13
R-77-106F	0.0518	80.4422	8.2	6.0	90.8491	0.9422	3826.	2.0	10.4069	0.2431	354.	1532.	477.	7.73
R-77-107F	0.0519	81.5031	17.3	12.6	91.3072	0.4563	3919.	2.0	9.7141	0.1319	389.	2796.	460.	8.21
R-77-108F	0.0519	81.6665	22.9	17.4	90.8634	0.3391	4028.	1.9	9.1969	0.1017	422.	3616.	485.	8.00
R-77-109F	0.0505	81.9073	13.3	9.7	93.1479	0.6216	4106.	1.8	11.2405	0.1627	352.	2288.	424.	9.32
R-77-110F	0.0519	80.5241	35.6	26.0	87.6655	0.2333	4138.	1.9	7.1314	0.0738	559.	4900.	640.	6.23
R-77-111F	0.0519	81.5778	35.2	25.7	90.6051	0.2331	4173.	1.9	8.4274	0.0745	477.	4914.	535.	7.52
R-77-112F	0.0519	80.2625	11.7	8.5	89.1933	0.7173	4195.	1.9	8.5303	0.1797	451.	2030.	600.	6.72
R-77-113F	0.0518	80.8918	13.0	9.5	90.9394	0.6468	4196.	1.8	10.0476	0.1650	402.	2230.	503.	3.03
R-77-114F	0.0519	81.0951	11.4	8.3	91.9317	0.7455	4228.	1.8	10.8466	0.1938	376.	2013.	474.	8.60
R-77-115F	0.0519	80.9287	23.0	16.8	88.5681	0.3712	4254.	1.8	7.6395	0.1047	536.	3471.	648.	6.33
R-77-116F	0.0518	80.9740	16.4	12.0	89.2559	0.5248	4287.	1.8	8.2919	0.1373	499.	2658.	630.	6.56
R-77-117F	0.0519	82.1921	11.9	8.7	94.6524	0.7301	4311.	1.8	12.4603	0.1700	333.	2108.	404.	10.27
R-77-118F	0.0519	82.4049	9.3	6.8	96.5027	0.9593	4420.	1.7	14.0079	0.2165	305.	1749.	378.	11.30
R-77-119F	0.0519	81.2715	9.0	6.6	93.6869	0.9949	4458.	1.7	12.4154	0.2219	346.	1682.	440.	9.58
R-77-120F	0.0505	81.2480	23.1	16.9	92.4702	0.4243	4832.	1.5	11.2216	0.1044	419.	3555.	482.	9.75
R-77-121F	0.0505	81.1304	16.5	12.0	93.5744	0.5991	4907.	1.5	12.4440	0.1369	380.	2724.	450.	10.52
R-77-122F	0.0519	81.3453	35.5	25.9	92.1236	0.2361	5054.	1.5	10.7833	0.0740	452.	5001.	502.	9.70
R-77-123F	0.0505	81.4780	12.9	9.4	95.7508	0.8093	5194.	1.4	14.2728	0.1605	351.	2266.	423.	11.82
R-77-124F	0.0518	81.3374	63.3	46.2	91.5869	0.1686	5315.	1.5	10.2496	0.0460	500.	7926.	537.	9.53
R-77-125F	0.0518	81.7597	11.4	8.3	97.1526	0.9385	5323.	1.5	15.3929	0.1830	333.	2067.	406.	12.64

Table C.4 (continued)

FIR NUMBER	P H, I	T M, O	F W	V W	T W, AVG	ΔT W	Q BTU/HR	RF	ΔT	FPS	Y	U O	H W	H* C	ΔT* C	DEG F
R-717-121F	0.0519	82.1337	12.8	9.3	98.3933	0.9370	5948.	1.3	16.2602	0.1679		352.	2275.	426.		13.46
R-717-122F	0.0532	82.7608	9.9	7.2	101.6909	1.2154	5985.	1.3	18.9301	0.2058		305.	1887.	371.		15.53
R-717-123F	0.0505	82.1178	16.2	11.8	97.0819	0.7503	6058.	1.2	14.9640	0.1385		390.	2741.	463.		12.60
R-717-124F	0.0519	82.4549	9.2	6.7	101.0950	1.3433	6176.	1.2	18.6901	0.2174		319.	1781.	399.		14.93
R-717-125F	0.0519	82.9027	62.7	45.8	96.0202	0.2017	6297.	1.2	13.1174	0.0469		462.	8044.	494.		12.28
R-717-126F	0.0519	82.1174	23.6	17.2	96.1393	0.5428	6372.	1.2	13.8219	0.1027		444.	3680.	513.		11.97
R-717-127F	0.0519	82.6452	63.5	46.3	96.6099	0.2017	6375.	1.2	13.9647	0.0465		440.	8145.	468.		13.13
R-717-128F	0.0506	82.6926	35.5	25.9	95.8152	0.3694	6507.	1.2	13.1225	0.0740		478.	5095.	533.		11.76
R-717-129F	0.0519	83.3975	12.7	9.2	102.1261	1.0746	6771.	1.1	18.5286	0.1689		345.	2305.	413.		15.78
R-717-130F	0.0519	83.2890	34.7	25.1	97.2725	0.3920	6779.	1.1	13.5936	0.0753		467.	5045.	521.		12.55
R-717-131F	0.0519	83.3777	23.7	17.3	98.4492	0.5807	6843.	1.1	15.0715	0.1024		437.	3734.	503.		13.11
R-717-132F	0.0531	83.1115	10.5	7.6	106.1807	1.3264	6903.	1.1	23.0693	0.1969		288.	2614.	343.		19.40
R-717-133F	0.0519	83.2178	16.6	12.1	100.4553	0.8486	7010.	1.1	17.2375	0.1160		392.	2830.	463.		14.59

Table C.5. Experimental data for externally fluted tube F, $FN_1 \sim 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)

RUN NUMBER	F N ₁	T H ₂ O	P GPM	V FPS	T °F	W WAVE	AT °F	Q BTU/HR	BP PSI	ΔT °F	Y	U O	H W	H [*] C	ΔT [*] C	DEG F
R-717-139F	0.1007	79.3117	37.2	27.1	81.7661	0.1277	2364.	6.4	3.4543	0.0713	659.	4908.	775.	2.94		
R-717-140F	0.1007	79.8597	26.3	19.2	83.0910	0.2097	2746.	5.5	4.2313	0.0941	625.	3748.	767.	3.45		
R-717-141F	0.1007	79.0724	18.8	13.7	83.9657	0.3024	2823.	5.4	4.8933	0.1234	556.	2874.	708.	3.84		
R-717-142F	0.1007	79.3124	9.0	6.6	85.6706	0.6402	2869.	5.3	6.3582	0.2219	435.	1613.	626.	4.45		
R-717-143F	0.1007	79.3115	11.6	8.4	85.1301	0.5015	2891.	5.2	5.8186	0.1814	479.	1967.	656.	4.25		
R-717-144F	0.1007	79.2008	13.7	10.0	84.7310	0.4237	2932.	5.2	5.5303	0.1582	511.	2250.	603.	4.14		
R-717-145F	0.1007	79.9129	63.2	46.1	83.3052	0.1046	3291.	4.6	4.3923	0.0467	722.	7568.	807.	3.93		
R-717-146F	0.1007	79.0614	36.3	26.5	83.9975	0.1986	3587.	4.2	4.9260	0.0727	702.	4873.	835.	4.14		
R-717-147F	0.1007	79.0909	24.2	17.6	84.4875	0.2995	3607.	4.2	5.3967	0.1006	644.	3533.	807.	4.30		
R-717-148F	0.1007	79.0601	17.1	12.5	85.5283	0.4375	3727.	4.1	6.4659	0.1327	555.	2694.	720.	4.99		
R-717-149F	0.1003	79.7022	8.5	6.2	88.7343	0.9282	3942.	3.8	9.4023	0.2316	421.	1571.	599.	6.35		
R-717-150F	0.1009	79.4055	14.2	10.4	86.9325	0.5842	4131.	3.7	7.4970	0.1540	532.	2339.	711.	5.60		
R-717-151F	0.1009	79.7162	11.7	8.5	87.8609	0.7233	4239.	3.6	8.1446	0.1797	499.	2015.	688.	5.90		
R-717-152F	0.1010	83.4281	9.1	5.9	91.2947	1.1321	4544.	3.3	8.8666	0.2423	494.	1522.	772.	5.67		
R-717-153F	0.1012	85.7174	17.7	12.9	93.6423	0.5461	4805.	3.1	7.9649	0.2093	581.	2886.	749.	6.18		
R-717-154F	0.1003	90.7191	17.0	12.4	98.2203	0.5740	4849.	3.1	7.5012	0.1336	623.	2715.	836.	5.59		
R-717-155F	0.1012	85.5223	35.4	25.9	92.2202	0.2805	4949.	3.0	6.6079	0.0741	712.	4998.	846.	5.64		
R-717-156F	0.1009	80.8250	23.7	17.3	87.6312	0.4247	5016.	3.0	6.8623	0.1022	704.	3539.	904.	5.35		
R-717-157F	0.1013	86.7826	8.1	5.9	98.4951	1.2441	5023.	3.0	11.7125	0.2412	413.	1585.	582.	8.32		
R-717-158F	0.1009	81.2227	10.4	7.6	90.9069	0.9831	5076.	3.0	9.6042	0.1983	504.	1856.	723.	6.76		
R-717-159F	0.1012	85.9415	11.6	8.5	95.8376	0.8740	5081.	2.9	9.8960	0.1809	495.	2087.	672.	7.29		
R-717-160F	0.1009	81.3150	7.4	5.4	92.7089	1.3780	5081.	3.0	11.3929	0.2593	430.	1432.	644.	7.60		
R-717-161F	0.1009	91.1128	11.6	8.4	90.3266	0.8877	5117.	2.9	9.2138	0.1814	535.	2022.	758.	6.51		
R-717-162F	0.1012	85.9286	23.7	17.3	93.5145	0.4366	5146.	2.9	7.6360	0.1024	645.	3643.	803.	6.17		
R-717-163F	0.1009	92.3024	14.3	10.5	92.2125	0.7239	5169.	2.9	9.9101	0.1529	503.	2424.	653.	7.63		
R-717-164F	0.1012	86.5546	9.2	6.7	97.7765	1.1265	5179.	2.9	11.2221	0.2174	445.	1753.	619.	8.06		

Table C.5 (continued)

FIRE NUMBER	P N, I	T N, O	P W	V W	T W, AVG	ΔT W	Q	R _F	ΔT	Y	U	H	H ⁴ C	ΔT^4 C
	GPB	DEG F	GPB	PPS	DEG F	DEG F	BTU/HR	DEG F	DEG F	PPS	---BTU/HR FT ² F---	W	C	DEG F
R-717-165F	0.1012	85.6084	62.8	45.8	91.9642	0.1686	5271.	2.8	6.3558	0.0469	799.	7890.	900.	5.64
R-717-166F	0.1009	81.1655	35.8	26.1	87.7797	0.2972	5292.	2.8	6.6131	0.0736	771.	4919.	933.	5.46
R-717-167F	0.1012	85.9138	18.7	13.4	93.4610	0.5302	5294.	2.8	7.5472	0.1256	676.	2968.	905.	5.64
R-717-168F	0.1010	83.2042	18.0	13.2	89.8757	0.5960	5355.	2.8	6.6716	0.1272	773.	2878.	1102.	4.68
R-717-169F	0.1012	96.1885	9.1	6.6	96.5011	1.2026	5445.	2.7	10.3126	0.2201	509.	1720.	757.	6.92
R-717-170F	0.1012	86.0905	14.1	10.3	94.5265	0.7777	5463.	2.7	9.4360	0.1549	624.	2421.	874.	6.02
R-717-171F	0.1012	95.6563	26.3	19.2	92.5063	0.4247	5551.	2.7	6.8500	0.0942	791.	3937.	1001.	5.34
R-717-172F	0.1010	83.3444	25.5	18.6	89.5727	0.4451	5651.	2.7	6.2284	0.0965	974.	3788.	1176.	4.63
R-717-173F	0.1011	83.4063	24.8	18.1	91.9299	0.4530	5654.	2.6	10.5236	0.0986	518.	3709.	610.	8.93
R-717-174F	0.1009	82.0330	63.5	46.3	88.3363	0.1850	5846.	2.6	6.3033	0.0465	894.	7806.	1024.	5.50
R-717-175F	0.1011	83.7025	10.7	13.6	94.5320	0.6365	5912.	2.5	10.0295	0.1238	536.	3027.	667.	8.54
R-717-176F	0.1011	85.6138	36.5	26.6	92.5606	0.3257	5921.	2.5	7.5557	0.0724	755.	5128.	901.	6.32
R-717-177F	0.1010	83.6041	13.5	9.9	91.9047	0.8828	5954.	2.5	8.3006	0.1600	691.	2312.	1035.	5.54
R-717-178F	0.1010	83.5228	37.7	27.5	89.3095	0.3176	5967.	2.5	5.7952	0.0705	994.	5176.	1263.	4.55
R-717-179F	0.1012	95.4559	37.4	27.3	92.2650	0.3206	5972.	2.5	6.8091	0.0710	845.	5220.	1030.	5.58
R-717-180F	0.1012	95.3909	66.8	48.8	91.7100	0.1316	6043.	2.5	6.3191	0.0446	921.	8281.	1051.	5.54
R-717-181F	0.1010	83.7447	9.5	6.9	93.2944	1.2937	6122.	2.4	9.5498	0.2131	618.	1748.	1017.	5.90
R-717-182F	0.1011	94.9387	38.0	27.7	92.5059	0.3251	6152.	2.4	7.5672	0.0701	783.	5294.	937.	6.12
R-717-183F	0.1003	80.1829	28.1	20.5	89.8331	0.4449	6230.	2.4	9.6502	0.092	622.	4103.	748.	8.02
R-717-184F	0.1012	85.3112	27.0	19.7	93.9888	0.4656	6248.	2.4	8.6774	0.0923	694.	4052.	857.	7.03
R-717-185F	0.1010	83.6783	66.7	48.7	88.8687	0.1926	6395.	2.2	5.1904	0.0447	1187.	8145.	1416.	4.35
R-717-186F	0.1011	84.1424	67.1	48.9	90.3873	0.2613	6722.	2.2	6.2449	0.0445	1037.	8248.	1206.	5.37
R-717-187F	0.1010	83.7043	67.5	49.2	90.2124	0.2013	6760.	2.2	6.5085	0.0443	1001.	8277.	1156.	5.63
R-717-188F	0.1009	80.6606	22.9	16.7	88.3139	0.5945	6794.	2.2	7.6532	0.1050	854.	3455.	1177.	5.55
R-717-189F	0.1009	80.8023	16.4	12.0	89.7619	0.8461	6911.	2.2	8.8996	0.1373	748.	2665.	1087.	6.12
R-717-190F	0.1009	81.6010	10.4	7.6	92.7079	1.3707	7069.	2.1	11.1067	0.1983	613.	1873.	964.	7.07

Table C.5 (continued)

FIR NUMBER	F N, I	T N, O	P W	Y W	T W, AVG	ΔT W	Q	RP	ΔT	Y	---BTU/HR FT ² P---			ΔT^A C
											U	H	H ^A C	DEG F
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR			FPS				
R-717-191P	0.1007	78.3637	39.8	29.0	89.5173	0.3591	7115.	2.1	10.6541	0.0676	643.	5407.	741.	9.25
R-717-192P	0.1009	80.5719	62.4	45.5	86.9690	0.2299	7142.	2.1	6.3971	0.0471	1076.	7643.	1275.	5.40
R-717-193P	0.1009	81.2135	12.6	9.2	91.3642	1.1397	7155.	2.1	10.1507	0.1694	679.	2177.	1039.	6.63
R-717-194P	0.1003	80.6066	35.5	25.9	87.4770	0.4105	7252.	2.1	6.8704	0.0740	1017.	4880.	1323.	5.28
R-717-195P	0.1009	81.6336	62.8	45.8	91.1011	0.2412	7605.	2.0	9.4704	0.0469	774.	7855.	869.	8.43
R-717-196P	0.1011	84.3520	10.6	7.8	99.3055	1.6065	8511.	1.9	14.5535	0.1941	548.	1978.	792.	10.35
R-717-197P	0.1010	83.0860	9.0	6.6	97.1564	1.9240	8666.	1.7	14.0704	0.2210	593.	1719.	963.	8.67
R-717-198P	0.1010	83.4019	37.0	27.0	92.9031	0.4751	8759.	1.7	9.5012	0.0716	888.	5195.	1096.	7.70
R-717-199P	0.1010	82.7050	16.4	26.5	94.4460	0.4897	8860.	1.7	11.6510	0.0726	733.	5162.	871.	9.81
R-717-200P	0.1009	81.3079	9.6	7.0	100.2132	1.8817	8959.	1.7	18.9053	0.2114	457.	1824.	632.	13.65
R-717-201P	0.1011	94.2457	22.7	16.6	95.9767	0.7943	8972.	1.7	11.7310	0.1059	737.	3565.	956.	9.04
R-717-202P	0.1011	94.6342	14.0	10.2	96.9112	1.3135	9166.	1.6	12.2840	0.1557	719.	2437.	1069.	8.26
R-717-203P	0.1009	79.7022	37.8	27.6	90.9322	0.4371	9175.	1.6	11.2300	0.0704	787.	5231.	945.	9.35
R-717-204P	0.1011	84.3169	9.4	6.8	100.6746	1.9735	9211.	1.6	16.3579	0.2143	542.	1799.	816.	10.88
R-717-205P	0.1009	80.8058	25.5	18.6	93.3935	0.7272	9215.	1.6	12.5336	0.0966	709.	3859.	890.	9.98
R-717-206P	0.1011	94.3797	17.4	12.7	97.4145	1.0662	9231.	1.6	13.0348	0.1310	682.	2903.	923.	9.63
R-717-207P	0.1009	80.9313	13.4	9.7	97.2755	1.3939	9271.	1.6	16.3441	0.1618	546.	2349.	737.	12.12
R-717-208P	0.1011	94.6341	63.0	46.0	94.4100	0.2364	9298.	1.6	9.7719	0.0468	917.	8008.	1050.	8.53
R-717-209P	0.1009	81.9580	18.7	13.6	95.3515	1.0021	9331.	1.6	13.3928	0.1230	671.	3045.	889.	10.11
R-717-210P	0.1011	94.3169	35.2	25.6	94.8716	0.5346	9357.	1.6	10.7547	0.0746	838.	5034.	1023.	8.76
R-717-211P	0.1011	84.6315	18.9	13.8	95.6374	0.9932	9398.	1.6	11.0059	0.1226	822.	3074.	1169.	7.74
R-717-212P	0.1011	83.8770	17.2	12.5	98.8335	1.1100	9481.	1.6	14.5585	0.1324	611.	2892.	798.	11.45
R-717-213P	0.1012	85.5350	8.0	5.8	104.3961	2.3924	9492.	1.6	18.8611	0.2446	495.	1608.	729.	12.54
R-717-214P	0.1012	85.1879	12.5	9.1	100.4419	1.5296	9531.	1.6	15.2541	0.1704	602.	2264.	854.	10.75
R-717-215P	0.1010	83.5390	67.3	49.1	93.1139	0.2917	9770.	1.5	9.5798	0.0444	982.	8304.	1130.	8.33
R-717-216P	0.1011	94.2334	13.4	9.8	101.0552	1.4677	9796.	1.5	16.8218	0.1613	561.	2399.	758.	12.45

Table C.5 (continued)

FUR NUMBER	F		T		V		T		ΔT		Q		RP		ΔT		Y		U		H		H*		ΔT*	
	N, I	N, O	DEG F	GPM	PPS	W	F	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
	GPM	DEG F	DEG F	GPM	PPS	W	F	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W	W
R-717-212P	0.1011	82.6849	26.3	19.2	95.6161	0.7514	9820.	1.5	11.5111	0.0942	793.	3999.	1017.	9.30												
R-717-212P	0.1011	84.6378	24.0	17.5	98.0205	0.8376	10078.	1.5	13.9027	0.1011	691.	3773.	867.	11.14												
R-717-212P	0.1012	85.2024	8.7	6.4	105.6110	2.3243	10089.	1.5	20.3875	0.2276	477.	1737.	686.	14.17												
R-717-220P	0.1012	85.0293	11.3	9.6	103.7613	1.8531	10898.	1.4	18.7330	0.1785	560.	2196.	742.	13.42												

Table C.6. Experimental data for externally fluted tube F, $P_{N,1} \sim 15.77 \times 10^{-6} \text{ m}^3/\text{s}$ (0.250 gpm)

Run Number	F N ₁ I	T N ₂ O	P W	V W	T W, AVG	ΔT W	Q	RP	ΔT	Y	U	H	R [*] C	ΔT^* C
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR		DEG F	FPS		---BTU/HR FT ² °F---		DEG F
R-717-221F	0.2474	76.1562	66.8	48.7	79.9595	0.0901	2994.	12.6	2.8033	0.0447	1029.	7714.	1208.	2.39
R-717-222F	0.2472	75.2691	66.6	48.6	78.2720	0.0959	3175.	11.9	3.0039	0.0448	1018.	7666.	1194.	2.56
R-717-223F	0.2475	76.5900	8.4	6.1	82.1838	0.7863	3205.	11.4	5.5939	0.2347	566.	1495.	976.	3.24
R-717-224F	0.2475	76.7499	37.5	27.4	80.2117	0.1826	3409.	11.0	3.4618	0.0708	949.	4899.	1209.	2.72
R-717-225F	0.2475	76.3390	51.4	37.5	79.6560	0.1446	3698.	10.2	3.3170	0.0551	1074.	6282.	1326.	2.69
R-717-226F	0.2476	76.9907	18.8	13.7	81.6202	0.4028	3769.	10.0	4.6294	0.1231	784.	2842.	1131.	3.21
R-717-227F	0.2476	77.0490	27.8	20.2	81.1376	0.2771	3829.	9.8	4.1196	0.0901	895.	3870.	1205.	3.06
R-717-228F	0.2475	76.9275	9.6	7.0	83.1760	0.8268	3936.	9.5	6.2486	0.2114	607.	1670.	1018.	3.72
R-717-229F	0.2473	75.9706	52.5	39.3	79.5253	0.1538	4023.	9.4	3.6547	0.0541	1060.	6391.	1300.	2.98
R-717-230F	0.2476	77.2575	19.4	13.4	82.4947	0.4716	4314.	8.7	5.2372	0.1254	794.	2805.	1159.	3.59
R-717-231F	0.2495	82.5283	9.3	6.0	89.7309	1.0675	4395.	8.4	7.2525	0.2379	582.	1538.	1006.	4.20
R-717-232F	0.2483	91.4007	18.2	13.3	86.6398	0.4865	4405.	8.4	5.2392	0.1264	910.	2846.	1185.	3.58
R-717-233F	0.2480	80.2858	66.5	48.5	83.8260	0.1361	4502.	8.3	3.5402	0.0448	1225.	7903.	1480.	2.93
R-717-234F	0.2484	81.9188	13.9	10.1	87.7973	0.6610	4566.	8.1	5.8786	0.1570	748.	2306.	1170.	3.76
R-717-235F	0.2475	77.0770	37.1	27.1	81.5995	0.2437	4590.	8.2	4.5275	0.0715	977.	4893.	1255.	3.52
R-717-236F	0.2476	77.3287	20.9	21.1	82.1772	0.3226	4638.	8.1	4.8485	0.0873	922.	4019.	1237.	3.61
R-717-237F	0.2482	70.7643	25.4	18.5	85.3163	0.3980	4899.	7.6	5.0519	0.0969	934.	3696.	1299.	3.63
R-717-238F	0.2480	80.0444	66.7	49.7	84.5146	0.1539	5110.	7.3	4.4706	0.0447	1101.	7956.	1301.	3.78
R-717-239F	0.2481	90.6523	37.5	27.4	85.4639	0.2794	5217.	7.1	4.8166	0.0708	1044.	5045.	1355.	3.71
R-717-240F	0.2482	81.2033	66.8	48.7	85.3559	0.1629	5413.	6.9	4.1526	0.0447	1256.	7997.	1521.	3.43
R-717-241F	0.2484	82.7594	52.7	38.5	87.6134	0.2111	5542.	6.7	4.8540	0.0539	1100.	6704.	1345.	3.97
R-717-242F	0.2484	82.0383	51.5	37.5	86.5750	0.2191	5615.	6.6	4.5367	0.0550	1192.	6539.	1495.	3.62
R-717-243F	0.2486	79.8551	66.9	48.7	83.9798	0.1695	5636.	6.6	4.1247	0.0446	1316.	7941.	1614.	3.36
R-717-244F	0.2482	81.1357	26.0	19.9	86.9314	0.4448	5751.	6.5	5.7957	0.0951	956.	3790.	1328.	4.17
R-717-245F	0.2480	80.2006	37.5	27.4	85.1957	0.3095	5760.	6.5	5.1051	0.0708	1087.	5043.	1429.	3.89
R-717-246F	0.2482	81.3064	10.0	13.9	87.7446	0.6141	5818.	6.4	6.4222	0.1219	973.	2969.	1296.	4.32

Table C.6 (continued)

FIN NUMBER	F	N, I	T	H, O	P	V	T	W, AVG	ΔT	Q	RP	ΔT	Y	U	H	R ^a	ΔT^a
	GPM	DEG F	DEG F	DEG F	GPM	PPS	DEG F	DEG F	DEG F	BTU/HR		DEG F	PPS	---	BTU/HR	FT ² F	DEG F
R-717-247P	0.2487	81.2016	66.8	48.7	85.5805	0.1759	5851.	6.3	4.3789	0.0446	1287.	8011.	1567.	3.60			
R-717-248P	0.2483	81.8691	13.4	9.7	89.5492	0.9090	6046.	6.1	7.6901	0.1618	758.	2258.	1210.	4.81			
R-717-249P	0.2486	92.2119	8.1	5.9	93.0495	1.5234	6115.	6.0	9.8356	0.2423	599.	1535.	1057.	5.57			
R-717-250P	0.2487	84.3714	41.9	30.5	90.3576	0.3057	6371.	5.8	5.9862	0.0649	1025.	5655.	1284.	4.78			
R-717-251P	0.2487	84.4939	9.9	6.4	93.9323	1.5244	6653.	5.5	9.7389	0.2266	658.	1649.	1182.	5.42			
R-717-252P	0.2487	83.8132	30.0	27.7	89.7751	0.3564	6746.	5.5	5.5618	0.0701	1090.	5220.	1420.	4.58			
R-717-253P	0.2490	86.1155	8.7	6.4	96.6481	1.5785	6852.	5.3	10.5326	0.2276	627.	1665.	1078.	6.13			
R-717-254P	0.2487	84.4118	18.3	13.3	92.1925	0.7915	7113.	5.2	7.7807	0.1259	801.	2943.	1320.	5.19			
R-717-255P	0.2487	34.4584	20.8	21.0	91.2411	0.5021	7206.	5.1	6.7827	0.0874	1023.	4216.	1402.	4.95			
R-717-256P	0.2490	95.4532	27.8	20.2	93.3202	0.5314	7342.	5.0	7.4670	0.0901	947.	4133.	1271.	5.57			
R-717-257P	0.2490	96.1072	19.0	13.9	94.6537	0.7931	7459.	4.9	8.4564	0.1221	856.	3071.	1227.	5.86			
R-717-258P	0.2485	72.5390	16.9	26.9	90.0656	0.4206	7725.	4.8	6.5365	0.0719	1140.	5103.	1517.	4.91			
R-717-259P	0.2483	91.3035	17.2	27.2	88.0729	0.4316	7997.	4.6	6.7693	0.0713	1118.	5086.	1515.	5.09			
R-717-260P	0.2482	31.3642	46.2	33.7	87.9837	0.3615	8309.	4.5	6.5195	0.0600	1228.	6037.	1586.	5.05			
R-717-261P	0.2483	91.7926	18.8	13.7	90.6720	0.9010	8411.	4.4	8.8794	0.1234	913.	2979.	1393.	5.86			
R-717-262P	0.2480	91.2653	66.8	48.7	87.4893	0.2550	8479.	4.4	6.2240	0.0446	1313.	8095.	1601.	5.10			
R-717-263P	0.2483	91.8441	20.1	20.5	99.5747	0.6059	8484.	4.4	7.7106	0.0892	1057.	4097.	1482.	5.51			
R-717-264P	0.2484	92.0713	9.4	6.8	93.9051	1.8563	9664.	4.3	11.8138	0.2148	705.	1740.	1283.	6.50			
R-717-265P	0.2481	90.6291	38.2	27.9	87.5995	0.4619	8796.	4.2	6.9715	0.0698	1214.	5180.	1642.	5.16			
R-717-266P	0.2481	90.5705	66.0	48.2	96.6402	0.2777	9131.	4.1	6.0697	0.0450	1445.	7585.	1815.	4.85			
R-717-267P	0.2483	92.2070	66.6	48.6	89.1232	0.2939	9590.	3.9	6.9161	0.0447	1334.	8147.	1631.	5.66			
R-717-268P	0.2484	82.6680	19.9	12.8	92.3153	1.0235	9626.	3.8	9.6473	0.1226	961.	3023.	1487.	6.24			
R-717-269P	0.2481	96.4807	26.0	18.9	95.6800	0.7540	9748.	3.8	9.1993	0.0351	1021.	3966.	1430.	6.57			
R-717-270P	0.2486	93.7750	8.9	6.5	97.4453	2.2569	9955.	3.7	13.7103	0.2247	760.	1693.	1293.	7.42			
R-717-271P	0.2485	82.9352	27.7	20.2	91.7726	0.7368	10162.	3.6	8.8374	0.0703	1108.	4095.	1584.	6.18			
R-717-272P	0.2493	97.4212	19.3	13.3	98.0759	1.1199	10193.	3.6	16.6548	0.1259	922.	3031.	1392.	7.06			

Table C.6 (continued)

FW NUMBER	F	N, I	T	N, O	P	V	T	W, AVG	ΔT	Q	RP	ΔT	F	FPS	U	H	H*	ΔT^*
	GPM	DEG F	GPM	PPS	DEG F	DEG F	W, AVG	DEG F	DEG F	BTU/HR		DEG F	FPS	---RTU/HR	O	W	C	DEG F
R-717-271F	0.2485	82.4129	45.5	33.2	91.1171	0.4519	10237.	3.6	7.9042	0.0607	1248.	6077.	1617.	6.10				
R-717-274F	0.2493	87.7266	13.6	10.0	99.7184	1.5119	10268.	3.5	11.9918	0.1591	825.	2417.	1329.	7.45				
R-717-275F	0.2486	83.4327	14.3	10.4	94.7846	1.4601	10359.	3.6	11.3520	0.1536	879.	2443.	1465.	6.81				
R-717-276F	0.2480	80.8798	18.3	13.3	91.7790	1.1644	10598.	3.5	10.5492	0.1259	932.	2936.	1441.	7.09				
R-717-277F	0.2486	83.3273	37.5	27.4	92.4171	0.5702	10658.	3.5	8.5099	0.0708	1195.	5240.	1601.	6.41				
R-717-278F	0.2490	80.7270	51.9	37.8	88.5213	0.4174	10753.	3.5	7.7988	0.0548	1328.	6636.	1708.	6.06				
R-717-279F	0.2491	81.2018	27.3	19.9	90.9864	0.7952	10800.	3.4	9.7246	0.0914	1070.	4028.	1518.	6.35				
R-717-280F	0.2481	81.0544	38.2	27.9	89.9004	0.5687	10816.	3.4	8.7460	0.0698	1191.	5241.	1594.	6.54				
R-717-281F	0.2499	80.5670	67.8	49.5	87.9691	0.3302	11142.	3.3	7.4021	0.0441	1450.	9211.	1804.	5.95				
R-717-282F	0.2489	85.5768	9.4	6.8	100.5278	2.4310	11347.	3.2	14.9511	0.2148	731.	1798.	1334.	8.19				
R-717-283F	0.2483	82.5257	8.6	6.3	98.4545	2.6631	11435.	3.2	15.9288	0.2296	692.	1645.	1244.	8.58				
R-717-284F	0.2481	84.9063	27.9	20.4	94.9455	0.8336	11595.	3.2	9.5602	0.0897	1121.	4190.	1546.	7.00				
R-717-285F	0.2490	86.2513	19.5	14.2	98.0915	1.2914	11537.	2.9	11.8472	0.1195	1019.	3192.	1530.	7.64				
R-717-286F	0.2491	80.0907	0.3	6.8	107.7562	2.9324	11618.	2.7	16.7755	0.2156	782.	1852.	1474.	8.90				

Table C.7. Experimental data for doubly fluted tube H, $F_{N,1} \sim 3.15 \times 10^{-6} \text{ m}^3/\text{s}$ (0.050 gpm)

RUN NUMBER	F N ₂ I	T N ₂ O	P W	V W	T W, AVG	ΔT W	Q	RP	ΔI	Y	U	H W	H* C	ΔT* C
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR		DEG F	FPS	---	BTU/HR	FT ² /P---	DEG F
R-717-100H	0.0519	90.1395	86.7	42.3	82.6858	0.0426	1841.	4.2	2.5473	0.0500	415.	596.8.	458.	2.31
R-717-101H	0.0519	82.1605	87.9	47.9	86.9965	0.0505	2563.	3.0	4.8261	0.0494	305.	6179.	327.	4.51
R-717-102H	0.0519	80.9058	40.9	20.0	84.7275	0.1262	2571.	3.0	3.8217	0.0911	387.	3310.	458.	3.23
R-717-103H	0.0519	82.6241	9.0	4.4	89.0053	0.6189	2773.	2.8	6.3817	0.7061	250.	1009.	373.	4.28
R-717-104H	0.0519	91.8639	26.6	13.0	86.4423	0.2124	2816.	2.7	4.5784	0.1285	353.	2369.	441.	3.67
R-717-105H	0.0519	82.6049	11.3	5.5	88.7235	0.5118	2867.	2.7	6.1249	0.2561	269.	1204.	383.	4.30
R-717-106H	0.0519	82.5859	14.1	6.9	89.6239	0.4391	3067.	2.5	6.0381	0.2142	292.	1438.	406.	4.41
R-717-107H	0.0519	82.2708	19.0	9.3	87.5657	0.3259	3088.	2.5	5.2950	0.1682	335.	1822.	444.	4.00
R-717-108H	0.0519	93.6810	9.1	4.5	92.3663	0.7514	3420.	2.2	8.6853	0.3023	226.	1039.	319.	6.17
R-717-109H	0.0519	83.2585	12.3	8.9	90.2991	0.3823	3480.	2.2	7.0396	0.1736	284.	1790.	360.	5.55
R-717-110H	0.0519	83.3597	11.3	5.5	91.5397	0.6317	3538.	2.2	8.1806	0.2561	249.	1222.	341.	5.96
R-717-111H	0.0519	83.3351	14.5	7.1	91.0578	0.4934	3558.	2.2	7.7227	0.2092	265.	1492.	347.	5.90
R-717-112H	0.0519	83.1031	26.7	13.0	89.6123	0.2738	3642.	2.1	6.5090	0.1282	322.	2416.	391.	5.36
R-717-113H	0.0519	92.5623	41.2	20.1	89.3495	0.1786	3659.	2.1	5.7974	0.0907	363.	3391.	424.	4.96
R-717-114H	0.0520	85.1465	26.2	12.8	92.7123	0.3236	4214.	1.8	7.5654	0.1304	320.	2414.	389.	6.23
R-717-115H	0.0519	84.9768	40.8	19.9	92.5398	0.2104	4271.	1.8	7.5680	0.0914	324.	3441.	371.	6.62
R-717-116H	0.0520	95.2375	18.9	9.2	93.6385	0.4552	4291.	1.8	8.4010	0.1628	294.	1873.	371.	6.65
R-717-117H	0.0520	85.8476	11.0	5.4	95.3214	0.8066	4405.	1.7	9.4744	0.2613	267.	1221.	377.	5.71
R-717-118H	0.0520	85.4190	14.9	7.3	94.6163	0.5966	4413.	1.7	9.1978	0.2050	276.	1551.	361.	7.02
R-717-119H	0.0519	94.4065	88.1	43.0	90.1849	0.1045	4582.	1.7	5.7784	0.0494	456.	6293.	504.	5.22
R-717-120H	0.0520	96.3041	8.0	3.9	97.4805	1.1637	4617.	1.7	11.1764	0.3374	237.	955.	355.	7.48
R-717-121H	0.0520	97.0173	19.2	9.4	95.9609	0.5218	4993.	1.5	8.8436	0.1668	324.	1917.	419.	6.85
R-717-122H	0.0520	85.6924	87.6	42.5	92.7234	0.1205	5224.	1.5	7.0115	0.0498	427.	6317.	469.	6.40
R-717-123H	0.0520	87.5305	13.7	6.7	97.5523	0.7708	5270.	1.4	10.0318	0.2183	302.	1477.	415.	7.30
R-717-124H	0.0521	87.9503	11.2	5.5	98.7254	0.9471	5283.	1.4	10.7752	0.2569	282.	1263.	401.	7.57
R-717-125H	0.0520	86.4117	25.8	12.6	94.8657	0.4155	5343.	1.4	8.4540	0.1317	363.	2416.	454.	6.76

Table C.7 (continued)

SUN NUMBER	F N, I	T N, O	P W	V W	T W, AVG	ΔT W	Q	RF	ΔI	Y	U O	H W	H* C	ΔT^* C
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR		DEG F	PPS	---BTU/HR	FT ² *P---	DEG F	
R-777-120H	0.0520	85.7693	40.5	19.8	93.5318	0.2670	5389.	1.4	7.7625	0.0918	399.	3443.	472.	6.56
R-777-127H	0.0521	98.1691	8.5	4.2	99.7635	1.3568	5763.	1.3	11.5993	0.3195	286.	1020.	455.	7.28
R-777-129H	0.0520	87.2256	10.3	3.9	96.2900	0.6487	5904.	1.3	9.0644	0.1736	374.	1846.	513.	6.62
R-777-129H	0.0521	98.1753	14.2	6.9	97.9731	0.8692	6119.	1.2	9.8029	0.2131	359.	1517.	524.	6.72
R-777-130H	0.0521	88.3488	11.1	5.4	99.0421	1.1099	6139.	1.2	10.6932	0.2587	330.	1256.	507.	6.95
R-777-131H	0.0520	86.8064	41.5	20.2	94.4049	0.3063	6325.	1.2	7.5986	0.0901	478.	3522.	584.	6.22
R-777-132H	0.0520	87.1698	18.4	9.0	97.4005	0.6924	6351.	1.2	10.2307	0.1726	357.	1867.	478.	7.63
R-777-133H	0.0520	87.2001	25.7	12.5	95.3564	0.4932	6394.	1.2	8.1562	0.1323	450.	2412.	598.	6.13
R-777-134H	0.0521	99.7841	8.9	4.3	101.7933	1.4527	6407.	1.2	13.0247	0.3100	233.	1062.	430.	8.41
R-777-135H	0.0520	87.3574	26.6	12.7	96.9465	0.4980	6439.	1.2	9.5891	0.1311	396.	2452.	488.	7.58
R-777-136H	0.0520	87.2304	87.0	42.5	93.8451	0.1482	6424.	1.2	6.6446	0.0490	558.	6353.	632.	5.84
R-777-137H	0.0521	88.1032	14.1	6.9	99.7265	0.9379	6567.	1.2	11.6233	0.2142	325.	1522.	454.	9.32
R-777-138H	0.0521	88.0421	11.3	5.5	100.3993	1.1708	6585.	1.2	12.3572	0.2552	306.	1281.	449.	8.43
R-777-139H	0.0521	98.7445	9.4	4.1	103.6943	1.6203	6806.	1.1	14.5798	0.3223	261.	1030.	394.	9.93
R-777-140H	0.0520	87.2603	41.2	20.1	96.3884	0.3344	6861.	1.1	9.1381	0.0906	432.	3538.	516.	7.64
R-777-141H	0.0520	87.2722	89.2	43.0	96.2906	0.1545	7226.	1.1	9.0184	0.0493	461.	6501.	508.	8.17

Table C.8. Experimental data for doubly fluted tube H, $P_{N,1} \sim 6.31 \times 10^{-6} \text{ m}^3/\text{s}$ (0.100 gpm)

ROW NUMBER	F	T	P	V	T	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP	ΔT	FPS	BTU/HR	ΔT	Q	RP</
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Table C.8 (continued)

FIR NUMBER	F N,I	T N,O	P W	V W	T W,AVG	ΔT W	Q	RP	ΔI	Y	---BTU/HR FT ² °P---			ΔT^*		
											U	H	W	H [*] C	C	C
	GPM	DEG F	GPM	PPS	DEG F	DEG F	BTU/HR		DEG F	FPS						DEG F
R-717-162H	0.1013	86.6091	14.0	6.8	92.4889	0.7235	5049.	2.9	5.8799	0.2148	493.	1464.	895.			3.24
R-717-162H	0.1013	86.8613	12.1	5.9	93.0668	0.8413	5066.	2.9	6.2055	0.2417	469.	1305.	900.			3.24
R-717-170H	0.1010	83.8163	88.3	43.1	97.1605	0.1301	5718.	2.6	3.3482	0.0493	981.	6204.	1243.			2.64
R-717-171H	0.1012	85.4586	26.3	12.9	90.1044	0.4424	5802.	2.6	4.6459	0.1296	718.	2395.	1194.			2.79
R-717-172H	0.1012	85.6330	19.1	9.3	90.7403	0.6130	5823.	2.6	5.0970	0.1678	657.	1856.	1241.			2.70
R-717-173H	0.1013	85.2248	40.7	19.9	89.4585	0.2997	6078.	2.5	4.2337	0.0915	825.	3383.	1222.			2.86
R-717-174H	0.1012	86.2474	10.9	5.3	92.6305	1.1236	6093.	2.4	6.4332	0.2631	543.	1196.	1375.			2.54
R-717-175H	0.1010	83.8352	88.2	43.0	87.8762	0.1420	6235.	2.4	4.0410	0.0493	897.	6225.	1094.			3.27
R-717-176H	0.1012	86.5427	8.8	4.3	93.6361	1.4309	6244.	2.4	7.0934	0.1126	506.	1012.	1514.			2.37
R-717-177H	0.1013	87.0668	87.3	42.6	91.6094	0.1460	6345.	2.3	4.5486	0.0497	802.	6294.	965.			3.78
R-717-178H	0.1012	86.3819	14.4	7.0	92.4819	0.9008	6475.	2.3	6.2000	0.2097	600.	1499.	1285.			2.90
R-717-179H	0.1012	85.5896	26.3	12.8	91.1829	0.5221	6836.	2.2	5.5824	0.1298	704.	2405.	1153.			3.41
R-717-181H	0.1013	84.6095	40.2	19.6	89.6567	0.3449	6906.	2.2	4.5632	0.0924	806.	3352.	1172.			3.39
R-717-182H	0.1015	89.2379	25.8	12.6	95.4536	0.5430	6983.	2.1	6.2152	0.1317	646.	2423.	1001.			4.01
R-717-183H	0.1012	86.2375	14.2	6.9	93.2127	1.0004	7074.	2.1	6.9952	0.2125	581.	1485.	1213.			3.35
R-717-184H	0.1015	89.3016	18.3	9.9	96.2643	0.7733	7084.	2.1	6.8827	0.1736	592.	1845.	1032.			3.95
R-717-185H	0.1013	84.6236	88.0	42.9	89.2352	0.1643	7195.	2.1	4.6116	0.0494	897.	6257.	1108.			3.73
R-717-186H	0.1012	86.6305	11.3	5.5	94.1354	1.2380	7214.	2.1	7.5509	0.2561	549.	1238.	1340.			3.09
R-717-187H	0.1013	86.8745	8.1	4.0	95.3252	1.8036	7292.	2.0	8.4507	0.3327	495.	959.	1586.			2.64
R-717-188H	0.1014	89.1957	39.8	19.4	94.9942	0.3721	7380.	2.0	5.7986	0.0931	732.	3420.	1023.			4.15
R-717-189H	0.1012	86.0962	41.2	20.1	91.8506	0.3868	7925.	1.9	5.7544	0.0967	792.	3454.	1139.			4.00
R-717-190H	0.1014	87.7003	89.3	43.1	92.5352	0.1809	7954.	1.9	4.7450	0.0493	963.	6384.	1205.			3.79
R-717-191H	0.1013	87.5016	13.5	9.0	94.5601	0.8806	8097.	1.8	7.0195	0.1722	663.	1845.	1271.			3.66
R-717-192H	0.1013	97.2914	26.2	12.9	93.7939	0.6280	8193.	1.8	6.5175	0.1302	722.	2431.	1195.			3.94
R-717-193H	0.1014	97.9953	13.2	6.5	95.9712	1.2637	8317.	1.8	7.9759	0.2251	599.	1421.	1366.			3.50

Table C.8 (continued)

FUN NUMBER	F N ₂ I	T N ₂ O	P W	V W	T W, AVG	ΔT W	Q	RP	ΔT	Y	U	H			ΔT ^a C
	GPM	DEG F	GPM	FPS	DEG F	DEG F	BTU/HR		DEG F	FPS	---	BTU/HR	FT ² °F---	H	DEG F
R-717-194H	0.1014	88.3225	11.3	5.5	96.9452	1.4907	8394.	1.8	0.5228	0.2552	565.	1259.	1405.		3.43
R-717-195H	0.1014	99.1878	40.5	19.7	95.0328	0.4360	8781.	1.7	5.8950	0.0920	856.	3463.	1276.		3.96
R-717-196H	0.1016	91.6672	8.1	3.9	102.5574	2.1925	8801.	1.7	10.8903	0.3343	464.	588.	1240.		4.08
R-717-197H	0.1016	91.3217	11.9	5.8	100.7225	1.5189	8968.	1.6	9.4008	0.2455	548.	1334.	1210.		4.26
R-717-198H	0.1014	89.1439	9.8	4.3	99.1675	2.0567	9024.	1.6	10.0237	0.3113	517.	1044.	1520.		3.41
R-717-199H	0.1016	91.2624	14.2	6.9	100.2626	1.2928	9141.	1.6	9.0002	0.2125	584.	1538.	1180.		4.45
R-717-200H	0.1016	90.8124	18.3	9.9	99.2132	1.0101	9217.	1.6	8.4008	0.1733	631.	1876.	1141.		4.64
R-717-201H	0.1016	91.3631	19.3	9.4	99.1493	0.9750	9352.	1.6	7.7858	0.1665	690.	1952.	1304.		4.12
R-717-202H	0.1016	90.8027	26.6	13.0	98.5017	0.7200	9544.	1.5	7.6990	0.1285	712.	2521.	1142.		4.80
R-717-203H	0.1016	91.3293	27.0	13.2	98.5513	0.7315	9834.	1.5	7.2235	0.1271	782.	2550.	1323.		4.27
R-717-204H	0.1015	90.4740	30.4	19.2	97.4998	0.5019	9840.	1.5	7.0257	0.0940	805.	3430.	1170.		4.83
R-717-205H	0.1014	89.1579	89.5	43.2	95.4359	0.2272	10004.	1.5	6.2780	0.0492	916.	6487.	1128.		5.10
R-717-206H	0.1015	90.4955	87.2	42.5	96.8012	0.2319	10064.	1.5	6.3158	0.0498	916.	6457.	1129.		5.12
R-717-207H	0.1017	92.7445	12.9	6.7	102.2091	1.4648	10076.	1.4	9.4436	0.2177	613.	1515.	1330.		4.36
R-717-208H	0.1017	92.2184	11.2	5.4	103.5632	1.8615	10339.	1.4	10.3498	0.2578	574.	1288.	1412.		4.21
R-717-209H	0.1018	90.1738	8.5	4.2	106.0298	2.4786	10528.	1.4	11.8560	0.3195	510.	1051.	1443.		4.19
R-717-210H	0.1017	92.2172	87.3	42.6	98.9630	0.2419	10603.	1.4	6.7507	0.0437	903.	6534.	1106.		5.51
R-717-211H	0.1017	92.1716	40.2	19.6	100.0039	0.5438	10877.	1.3	7.8293	0.0925	798.	3529.	1143.		5.47
R-717-212H	0.1017	92.8953	26.8	13.1	101.9141	0.8475	11293.	1.3	9.0288	0.1290	719.	2573.	1144.		5.67
R-717-213H	0.1019	94.1756	8.3	4.0	107.4431	2.7600	11401.	1.3	13.2675	0.3267	494.	1034.	1355.		4.84
R-717-214H	0.1019	92.5045	19.4	9.0	103.6442	1.2551	11511.	1.3	10.0637	0.1726	657.	1524.	1206.		5.49
R-717-215H	0.1017	92.1420	13.4	6.5	104.1419	1.7333	11529.	1.3	10.9999	0.2232	602.	1491.	1303.		5.09
R-717-216H	0.1018	92.7515	10.9	5.3	105.8639	2.1560	11673.	1.2	12.1175	0.2631	554.	1275.	1312.		5.11
R-717-217H	0.1018	92.9976	14.4	7.0	105.0707	1.6326	11697.	1.2	11.0731	0.2103	607.	1590.	1215.		5.44
R-717-218H	0.1019	94.4397	11.2	5.5	106.4455	2.1158	11801.	1.2	12.0058	0.2569	565.	1309.	1127.		5.11
R-717-219H	0.1010	91.8135	41.4	20.2	100.2391	0.5743	11835.	1.2	8.4256	0.0903	807.	3618.	1148.		5.92

Table C.8 (continued)

FURN NUMBER	F		T		P		V		T		R,AVG		ΔT		Q		RP		ΔT		Y		U		H		H*		ΔT*	
	N,I	N,O	DEG F	GPM	FPS	GPM	FPS	W	W	DEG F	DEG F	DEG F	DEG F	BTU/HR	BTU/HR	DEG F	FPS	DEG F	FPS	DEG F	FPS	DEG F	FPS	O	W	W	C	C	C	
R-717-223H	0.1017	93.2668	18.6	9.1	103.4637	1.2928	11978.	1.2	10.2019	0.1712	675.	1938.	1258.	5.47																
R-717-223H	0.1017	92.9666	28.5	13.9	102.2571	0.8660	12308.	1.2	9.2905	0.1216	761.	2714.	1215.	5.82																
R-717-223H	0.1017	95.2966	9.2	4.5	100.9100	2.7267	12600.	1.1	13.6134	0.2087	532.	1139.	1406.	5.15																

Table C.9. Experimental data for doubly fluted tube II, $F_{N,1} \sim 15.77 \times 10^{-6} \text{ m}^2/\text{s}$ (0.250 gpm)

FUR NUMBER	F	N ₂ O	T	P	V	W	T	W, AVG	ΔT	Q	RP	ΔT	FPS	---BTU/HR FT ² F---			
														DEG F	H	H*	DEG F
	GPM	DEG F		GPM	PFS		DEG F		DEG F	BTU/HR					W	C	
R-717-227H	0.2490	94.7968		25.5	12.4		88.7692		0.2638	3349.	11.0	3.9724	0.1331	484.	2317.	671.	2.87
R-717-224H	0.2489	84.5217		40.6	19.8		89.4040		0.1680	3396.	10.8	3.8023	0.0917	503.	3355.	628.	3.11
R-717-225H	0.2491	85.5882		8.7	4.3		90.9254		0.8083	3509.	10.4	5.3372	0.3140	378.	993.	765.	2.63
R-717-226H	0.2491	95.1720		19.1	9.3		89.6156		0.3702	3525.	10.4	4.4635	0.1675	454.	1849.	674.	3.01
R-717-227H	0.2491	85.5944		11.3	5.5		90.3341		0.6268	3540.	10.3	4.7597	0.2544	427.	1222.	866.	2.54
R-717-228H	0.2491	85.3369		14.1	6.9		90.0594		0.5074	3565.	10.3	4.7226	0.2136	434.	1453.	720.	2.85
R-717-229H	0.2493	83.7693		37.7	42.8		86.9705		0.0933	4291.	8.6	3.1012	0.0496	795.	6166.	960.	2.57
R-717-230H	0.2494	97.0663		14.2	6.9		92.6190		0.6155	4338.	8.4	5.5327	0.2131	451.	1477.	759.	3.29
R-717-231H	0.2494	87.2616		11.6	5.7		92.9344		0.7535	4344.	8.4	5.6228	0.2502	444.	1259.	837.	2.98
R-717-232H	0.2494	97.2493		9.3	4.6		93.4505		0.9155	4345.	8.4	6.2011	0.2975	403.	1062.	813.	3.07
R-717-233H	0.2494	86.9307		26.0	12.7		91.4565		0.3176	4372.	8.3	4.5259	0.1709	555.	2388.	804.	3.13
R-717-234H	0.2494	96.9655		19.5	9.5		92.1161		0.4615	4469.	8.2	5.1506	0.1652	499.	1899.	767.	3.35
R-717-235H	0.2494	96.9864		39.8	19.4		91.2688		0.2160	4670.	7.8	4.3824	0.0913	612.	3349.	809.	3.32
R-717-236H	0.2496	89.2096		19.6	9.6		94.5133		0.5902	5771.	6.3	6.2136	0.1640	534.	1937.	843.	3.93
R-717-237H	0.2496	99.2673		25.9	12.6		94.0749		0.4544	5853.	6.2	5.7876	0.1115	581.	2416.	856.	3.93
R-717-238H	0.2493	89.4712		11.3	5.5		97.1393		1.0466	5862.	6.2	7.6588	0.2561	440.	1257.	824.	4.09
R-717-239H	0.2504	92.5408		11.3	5.5		100.0513		1.0595	5934.	6.1	7.5105	0.2561	454.	1275.	864.	3.95
R-717-240H	0.2491	90.5793		9.1	4.5		97.9773		1.3269	6038.	6.0	8.3979	0.3023	413.	1669.	851.	4.08
R-717-241H	0.2503	91.9546		18.5	9.0		99.3203		0.6579	6065.	5.9	6.3657	0.1719	548.	1883.	893.	3.90
R-717-242H	0.2494	87.3610		87.8	42.8		91.7353		0.1396	6099.	6.0	4.3741	0.0895	801.	6326.	964.	3.64
R-717-243H	0.2497	80.9777		14.2	6.9		96.1113		0.8746	6164.	5.9	7.1936	0.2131	492.	1503.	873.	4.06
R-717-244H	0.2503	92.2398		14.1	6.9		99.3136		0.8905	6234.	5.8	7.0798	0.2142	506.	1519.	910.	3.94
R-717-245H	0.2561	91.3318		25.8	12.6		97.2473		0.4367	6246.	5.8	5.9155	0.1319	607.	2442.	907.	3.96
R-717-246H	0.2505	93.5010		8.6	4.2		102.5985		1.5408	6616.	5.4	9.0975	0.3167	418.	1043.	895.	4.25
R-717-247H	0.2498	89.2905		41.5	20.3		95.1186		0.3288	6800.	5.3	5.8381	0.0901	669.	3538.	835.	4.37
R-717-248H	0.2503	92.0556		40.6	19.8		97.9860		0.3473	7027.	5.1	5.9304	0.0916	681.	3527.	917.	4.41

Table C.9 (continued)

FUN NUMBER	P H ₂ O	T H ₂ O	P V	V W	T W, AVG	ΔT W	Q BTU/HR	RP	ΔI	Y	U O	H W	H ^a C	ΔT ^a C
	GPM	DEG F	GPM	FPS	DEG F	DEG F	BTU/HR			FPS	---	BTU/HR	FT ² ·F	---
R-77-240H	0.2503	92.0789	19.1	9.3	99.7383	0.8260	7845.	4.6	7.7194	0.1678	584.	1943.	974.	4.63
R-77-250H	0.2503	92.4270	11.5	5.6	101.6779	1.3997	7946.	4.5	9.2509	0.2519	494.	1306.	993.	4.60
R-77-251H	0.2503	92.2323	14.3	7.0	100.9348	1.1186	7962.	4.5	8.6025	0.2114	532.	1550.	979.	4.67
R-77-252H	0.2503	92.3777	25.9	12.6	99.4125	0.6191	7990.	4.5	7.0348	0.1313	653.	2478.	1005.	4.57
R-77-253H	0.2503	92.4406	9.2	4.5	102.5524	1.7650	8073.	4.4	10.1118	0.3011	459.	1097.	1035.	4.48
R-77-254H	0.2497	89.3293	87.8	42.8	94.5594	0.1932	8222.	4.4	5.2301	0.0495	904.	6418.	1112.	4.25
R-77-255H	0.2499	90.3268	40.5	19.8	96.5003	0.4101	8269.	4.4	6.1734	0.0919	770.	3491.	1090.	4.36
R-77-256H	0.2504	93.0694	87.8	42.8	98.9073	0.1912	8355.	4.3	5.8384	0.0495	822.	6558.	987.	4.86
R-77-257H	0.2505	93.2233	40.8	19.9	100.0277	0.4174	8475.	4.2	6.8045	0.0914	716.	3572.	976.	4.99
R-77-258H	0.2499	90.1190	87.6	42.7	96.2191	0.1959	8541.	4.2	6.6992	0.0496	805.	6460.	965.	5.09
R-77-259H	0.2493	93.9199	40.6	19.8	97.4765	0.4261	8621.	4.2	7.5566	0.0916	656.	3518.	872.	5.68
R-77-260H	0.2497	99.2493	87.7	42.8	95.2779	0.2031	8866.	4.1	6.0286	0.0496	845.	6435.	1024.	4.97
R-77-261H	0.2503	92.5663	9.9	4.3	105.3636	2.0367	9031.	4.0	12.7973	0.3097	406.	1684.	808.	6.43
R-77-262H	0.2502	91.7787	19.6	9.1	101.6191	1.6039	9301.	3.9	9.0895	0.1712	541.	1921.	864.	6.19
R-77-263H	0.2507	94.4333	8.4	4.1	106.7008	2.2392	9406.	2.8	12.2375	0.3223	440.	1045.	1001.	5.40
R-77-264H	0.2503	92.3199	11.7	5.7	103.8959	1.6139	9416.	2.8	11.5670	0.2478	468.	1341.	873.	6.20
R-77-265H	0.2503	92.2371	14.2	6.9	103.3063	1.3413	9453.	2.8	11.0692	0.2331	491.	1556.	846.	6.42
R-77-266H	0.2504	91.4558	25.6	12.5	100.6956	0.7446	9497.	2.8	9.2298	0.1327	591.	2468.	867.	6.29
R-77-267H	0.2506	93.9022	11.5	5.6	105.0529	1.6696	9595.	3.7	11.0698	0.2511	498.	1331.	990.	5.56
R-77-268H	0.2504	93.1578	87.9	42.8	99.4707	0.2323	10150.	3.5	6.3330	0.0495	924.	6576.	1137.	5.13
R-77-269H	0.2502	92.1769	26.5	12.9	99.7194	0.7688	10155.	3.5	7.5414	0.1289	774.	2529.	1106.	4.47
R-77-270H	0.2505	93.7084	14.2	6.9	103.0995	1.4728	10300.	3.4	9.3911	0.2311	635.	1555.	1393.	4.28
R-77-271H	0.2502	91.6522	25.7	12.6	100.9363	0.9127	10412.	3.5	9.2841	0.1321	645.	2482.	995.	6.07
R-77-272H	0.2504	93.1850	18.6	9.1	101.7526	1.1306	10559.	3.4	8.5676	0.1712	708.	1923.	1390.	4.37
R-77-273H	0.2502	92.1141	18.2	8.9	102.4198	1.1812	10696.	3.4	10.3047	0.1744	597.	1894.	1027.	5.98
R-77-274H	0.2497	89.3117	87.6	42.8	95.2443	0.2475	10797.	3.4	5.9326	0.0496	1046.	6422.	1335.	4.65

Table C.9 (continued)

FUR NUMBER	F		T		P		V		T		Q		RP		ΔT		Y		U		H		R ^A		ΔT ^A	
	N, I	N, O	DEG F	GPM	W	W	W	W	DEG F	DEG F	BTU/HR	BTU/HR	DEG F	DEG F	DEG F	DEG F	PFS	PFS	---BTU/HR	PT ² F---	W	B	R ^A	C	ΔT ^A	C
R-717-275H	0.2499	90.4239	40.5	19.7	97.1639	0.5412	10901.	3.2	6.7449	0.0920	929.	3500.	1436.	4.36												
R-717-276H	0.2505	91.5581	87.9	42.9	99.8199	0.2505	10967.	3.1	6.2319	0.0494	1003.	6599.	1258.	5.01												
R-717-277H	0.2504	92.1972	11.6	5.7	105.5310	1.9384	11219.	2.2	12.3503	0.2494	522.	1343.	1082.	5.96												
R-717-278H	0.2505	93.3070	8.8	4.3	107.0752	2.5600	11232.	3.2	13.6683	0.3112	472.	1084.	1125.	5.74												
R-717-279H	0.2504	93.0156	14.4	7.0	104.7009	1.5856	11361.	2.2	11.6651	0.2103	560.	1587.	1055.	6.19												
R-717-280H	0.2513	98.0291	9.9	4.3	111.3812	2.6248	11619.	3.0	13.3541	0.3087	501.	1114.	1248.	5.36												
R-717-281H	0.2509	95.8925	39.5	19.3	103.9771	0.5920	11646.	3.1	7.9846	0.0917	838.	3547.	1223.	5.47												
R-717-282H	0.2512	97.5966	26.6	12.7	106.9610	0.9353	12092.	2.9	9.2764	0.1311	749.	2570.	1224.	5.68												
R-717-283H	0.2514	99.3042	11.2	5.5	111.0211	2.1698	12204.	2.9	12.6369	0.2552	555.	1345.	1231.	5.70												
R-717-284H	0.2513	98.1818	14.4	7.0	110.1479	1.7395	12496.	2.8	11.9641	0.2097	600.	1631.	1177.	6.10												
R-717-285H	0.2513	97.9171	18.2	8.9	109.1923	1.4121	12786.	2.8	11.2753	0.1744	652.	1953.	1173.	6.27												

Appendix D

UNCERTAINTIES

D.1 Measurement Uncertainties

This appendix was written in order to qualify the accuracy in the experiment measurements and calculated results made in this study and reported in previous sections of this report. All errors in fluid property data obtained from the handbooks^{15,20} were neglected in this analysis, based on the assumption that these errors were negligible in comparison to the measurement errors. Also, measurement errors due to the actual physical location of the instrumentation in the system and errors due to system design (i.e., conduction of heat through the head section flanges, condensation on the evaporator module shell wall, etc.) were neglected. These assumptions appear reasonable since extreme care was exercised in system design and since many measurements were checked against independent instrument measurements. Each data point was screened by the author for measurement accuracy. Questionable data or results in obvious error were eliminated from the evaluations made in this study. Methods used for determining uncertainty were obtained from the literature.^{21,22,23}

For measurements made in this study, three sources of measurement uncertainty were assumed

1. Actual measurement device
 - A. thermistors for temperature measurements
 - B. vortex shedding flowmeter for water flowrates
 - C. integral orifice meter for ammonia flowrates

2. Readout of measurements

- A. digital multimeter for temperature measurements
- B. digital counter/timer for water flowrates
- C. pressure gauge for ammonia flowrates

3. Individual operating facility (technician)

- A. number bias
- B. recording values
- C. parallax for reaaading pressure gauge

The uncertainty of each measurement device and instrument was based on manufacturer's recommendations and on the assumption that each instrument was within calibration limits. The primary measurement uncertainties based on the square law for independent errors are listed in Table D.1.

D.2 Uncertainty in Results for Heat Load Calculations

The primary formula used for determination of heat load is given by Eq. (5.3):

$$Q = \dot{m}_w C_{p,w} \Delta T = \dot{m}_w C_{p,w} (T_{w,in} - T_{w,out}). \quad (5.3)$$

If we neglect errors due to fluid property uncertainty, differentiate Eq. (5.3) partially while noting that errors are independent (assuming each is normally distributed), and nondimensionalize the resulting equation, we get

$$\frac{dQ}{Q} = \left[\left(\frac{d(\dot{m}_w)}{\dot{m}_w} \right)^2 + \left(\frac{d(T_{w,in})}{T_{w,in} - T_{w,out}} \right)^2 + \left(\frac{d(T_{w,out})}{T_{w,in} - T_{w,out}} \right)^2 \right]^{1/2} \quad (D1)$$

Table D1. Measurement uncertainties

D1.1 Temperature measurements, Ω	
Thermistors	4200 ± 0.11^a
Multimeter	4200 ± 0.55^a
Operator	4200 ± 0.15^a
Total for temperatures in range of 4200 Ω (80°F)	4200 ± 0.58^a $(80 \pm 0.0065)^a$
Percent of temperature measurement	$\pm 0.014\%$
D1.2 Water flowrate measurements at lowest flows, pulses/min	
Flowmeter, pulses/min	1000 ± 2.5^a
Counter, pulses/min	1000 ± 4.0^a
Operator, pulses/min	1000 ± 10.0^a
Total for flow measure- ments in range of 1000 pulses/min (8 gpm)	1000 ± 11.1^a $(8.0 \pm 0.09)^a$
Percent of flow measure- ment	± 1.110
D1.3 Water flowrate measurement at intermediate flows, pulses/min	
Flowmeter, pulses/min	7000 ± 17.5^a
Counter, pulses/min	7000 ± 19.0^a
Operator, pulses/min	7000 ± 10.0^a
Total for flow measurements in range of 7000 pulses/ min (55 gpm)	7000 ± 27.7 $(55.0 \pm 0.22)^a$
Percent of flow measure- ment	± 0.39
D1.4 Water flowrate measurement at highest flows, pulses/min	
Flowmeter, pulses/min	12000 ± 30^a
Counter, pulses/min	12000 ± 32^a
Operator, pulses/min	12000 ± 10^a
Total for measurements in range of 12000 pulses/min (95 gpm)	12000 ± 45^a $(95 \pm 0.35)^a$
Percent of flow measure- ment	± 0.37
D1.5 Ammonia flowrate measurement (3 to 15 psi)	
Flowmeter system reading, %	$0-100 \pm 0.5^a$
Operator, %	$0-100 \pm 2.0^a$
Total flow measurement, %	$0-100 \pm 2.1$ of reading or ± 5 of actual flow

^aRatio or Odds of 20 to 1.

where

$$\frac{dQ}{Q} = \text{uncertainty in heat load determination}$$

$$\frac{d(\dot{m}_w)}{\dot{m}_w} = \text{uncertainty due to contribution of water flowrate measurement}$$

$$\frac{d(T_{w,in})}{T_{w,in} - T_{w,out}} = \text{uncertainty due to the contribution of the measured inlet water temperature}$$

$$\frac{d(T_{w,out})}{T_{w,in} - T_{w,out}} = \text{uncertainty due to the contribution of the measured outlet water temperature.}$$

Equation (D1), called the nondimensional second-power equation, may be used to determine the uncertainty in the calculated heat load for each individual run documented in Appendix C, with the interval of the result having the same odds (20 to 1). The same approach was used in the following sections for determining uncertainties.

D.3 Uncertainties in Results for Water Velocity Calculations

The water velocity through the evaporator tube was determined from:

$$V_w = F_w / A_{i,cs} , \quad (D2)$$

where

$$A_{i,cs} = \frac{\pi}{4} (D_i^2 - D_r^2) . \quad (D3)$$

The measurement uncertainty in the cross-sectional flow area may be

represented by:

$$\frac{dA_{i,cs}}{A_{i,cs}} = \pm 0.5\% \quad (20 \text{ to } 1).$$

Thus, the uncertainty in results for water velocity calculations are:

$$\frac{dV_w}{V_w} = \left[\left(\frac{dF_w}{F_w} \right)^2 + \left(\frac{dA_{i,cs}}{A_{i,cs}} \right)^2 \right]^{1/2} . \quad (D4)$$

In like manner, the uncertainty in $\dot{V}$ values used in the Wilson plot may be determined from:

$$\frac{dY}{Y} = 0.8 \left[\frac{dV_w}{V_w} \right] . \quad (D5)$$

D.4 Uncertainties in Results for Overall Heat Transfer Coefficient Calculations

The overall coefficient in the evaporator may be calculated from Eq. (5.1):

$$U_o = \frac{Q}{A_{t,o} \overline{\Delta T}} \quad (5.1)$$

where the average temperature difference ($\overline{\Delta T}$) is given by:

$$\overline{\Delta T} = \left[\frac{T_{w,in} + T_{w,out}}{2} \right] - T_{N,o} . \quad (5.2)$$

Using an approach similar to that used in Sect. D2, the uncertainty in the overall coefficients may be determined from the nondimensional

equation:

$$\frac{dU_o}{U_o} = \left[\left(\frac{dQ}{Q} \right)^2 + \left(\frac{dA}{A} \right)^2 + \left(\frac{d(\overline{\Delta T})}{\overline{\Delta T}} \right)^2 \right]^{1/2} . \quad (D6)$$

Assuming that the average temperature difference uncertainty $d(\overline{\Delta T})$ is given by

$$d(\overline{\Delta T}) = \left[\left(\frac{\Delta T_{w,in}}{2} \right)^2 + \left(\frac{\Delta T_{w,out}}{2} \right)^2 + \left(\frac{\Delta T_{N,o}}{2} \right)^2 \right]^{1/2} , \quad (D7)$$

then from Table D1:

$$\begin{aligned} d(\overline{\Delta T}) &= \left[\left(\frac{0.0065}{2} \right)^2 + \left(\frac{0.0065}{2} \right)^2 + (0.0065)^2 \right]^{1/2} (^\circ F) \\ &= 0.0080^\circ F. \end{aligned} \quad (D8)$$

Utilizing Eq. (D2), the results of the previous section, and Eq. (D4), the uncertainty in the determined values of the overall coefficient may be calculated. Since the Wilson plot is constructed from calculated values of both the overall coefficient, Eq. (D6) and the water velocity, Eq. (D5), then the uncertainty in results from the Wilson plot are propagated from uncertainties in these values, along with uncertainties inherent with the Wilson plot model.

D.5 Calculation and Tabulation of Uncertainty Values

Table D2 presents results of uncertainty evaluations for evaporation of ammonia outside tube A. The data spans the parameter ranges covered by this experimental study and the uncertainties are assumed to be representative of those from experiments with tube F and tube H.

Table 12. Experiment values, results, and uncertainties (20 to 1)

Run number	F_{N1} gpm (+ %)	F_w gpm (+ %)	Q Btu/h (+ %)	ΔT °F (+ %)	$Btu/h \cdot ft^2 \cdot ^\circ F$ (+ %)	$\frac{Y}{(fps)^{-0.8}}$ (+ %)
R-717-100A	0.0506 (5)	84.7 (0.4)	2737 (14.2)	3.2493 (0.3)	805 (14.2)	0.0470 (0.5)
R-717-101A	0.0519 (5)	8.9 (1.1)	3128 (1.7)	6.4918 (0.2)	460 (1.8)	0.2848 (1.2)
R-717-138A	0.0520 (5)	8.9 (1.1)	6314 (1.3)	11.8670 (0.1)	508 (1.4)	0.2860 (1.2)
R-717-141A	0.0520 (5)	85.6 (0.4)	6752 (5.8)	7.6698 (0.2)	841 (5.9)	0.0466 (0.5)
R-717-146A	0.1002 (5)	93.4 (0.4)	2705 (15.8)	3.8773 (0.3)	666 (15.8)	0.0434 (0.5)
R-717-151A	0.1003 (5)	9.9 (1.1)	3542 (1.7)	6.2879 (0.2)	538 (1.8)	0.2609 (1.2)
R-717-215A	0.01008 (5)	9.7 (1.1)	9823 (1.2)	14.3222 (0.1)	655 (1.3)	0.2659 (1.2)
R-717-218A	0.1007 (5)	93.5 (0.4)	10343 (4.2)	7.5841 (0.2)	1303 (4.3)	0.0434 (0.5)
R-717-225A	0.2465 (5)	9.1 (1.1)	3107 (1.7)	5.4301 (0.2)	547 (1.8)	0.2789 (1.2)
R-717-227A	0.2465 (5)	94.0 (0.4)	3138 (13.7)	3.1091 (0.3)	964 (13.7)	0.0432 (0.5)
R-717-287A	0.2481 (5)	94.5 (0.4)	11728 (3.7)	7.2962 (0.2)	1535 (3.8)	0.0431 (0.5)
R-717-289A	0.2489 (5)	14.5 (1.1)	11949 (1.2)	13.3809 (0.1)	853 (1.3)	0.1930 (1.2)

D6. Uncertainties in the Composite Heat Transfer Coefficients
and the Composite Temperature Differences

The uncertainty intervals for the composite heat transfer coefficients and composite temperature differences are not easily determined. As detailed in Appendix A, the composite coefficient (h_c^*) presented as experiment results in Appendix B is an average value of the Y-intercept value (a_0) of several Wilson plot lines. Each of these Wilson plot lines, in turn, were least square fits to several data points on the Wilson plot. Also, the Wilson plot method is based upon constant heat duty data points. Since a constant heat duty is difficult to obtain in practice or at an experimental facility, further result uncertainties occur. Lastly, the Wilson plot method for determining composite heat transfer coefficient (h_c^*) is only as good as the model used for the method, which in this case is the Reynolds analogy. According to the literature,¹⁰ the accuracy of predictions for laminar or turbulent flow heat transfer coefficients obtained from any available equation or graph may be no better than 30 percent. For all of these reasons, it is very difficult to determine a meaningful uncertainty interval without undertaking an exhaustive statistical analysis. Therefore, a more reasonable and realistic method of determining an uncertainty interval may in fact be to utilize engineering judgement. Thus, in the author's judgement, the uncertainty interval for the composite heat transfer coefficients (h_c^*) and the composite temperature differences (ΔT_c^*) may be expressed by the values commonly given in the heat transfer literature:

Composite heat transfer coefficients $h_c^* \pm 15\%$ (20 to 1)

Composite temperature differences $\Delta T_c^* \pm 15\%$ (20 to 1).

Appendix E

SI CONVERSION FACTORS

An attempt has been made to present all key tables and figures in dual units (ACU and SI). The following conversion factors may be used to convert from ACU to SI units:

<u>To convert from</u>	<u>To</u>	<u>Multiply by</u>
Btu/h	W	0.2929
Btu/h·ft ²	W/m	3.152
Btu/h·ft·°F	W/m·K	1.730
Btu/h·ft ² ·°F	W/m ² ·K	5.675
Btu/lb _m	J/kg	2.324 x 10 ³
Btu/lb _m ·°F	J/kg·K	4.184 x 10 ³
ft	m	0.3048
ft ²	m ²	0.0929
ft/h ²	m/s ²	2.35 x 10 ⁻³
ft/s	m/s	0.3048
gpm	m ³ /s	6.309 x 10 ⁻³
in.	cm	2.54
lb _f /ft	N/m	14.59
lb _m /ft ³	kg/m ³	16.02
lb _m /h·ft	Pa·s	4.134 x 10 ⁻⁴
lb _m /h·ft ²	Pa·s/m	1.356 x 10 ⁻³
psia	Pa	6.895 x 10 ³
Δ(°F)	Δ(K) or Δ(°C)	0.5556

Temperature conversion: $T(K) = 5/9 \times [T(^{\circ}F) - 32] + 273.15$

$T(^{\circ}C) = 5/9 \times [T(^{\circ}F) - 32]$

VITA

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