

A T H E S I S

on

THE UTILIZATION OF WASTE HEAT IN INTERNAL COMBUSTION ENGINES

Presented to

THE FACULTY OF THE ENGINEERING DEPARTMENT

of

THE UNIVERSITY OF TENNESSEE

For the Degree of

BACHELOR OF SCIENCE IN MECHANICAL ENGINEERING

By

Verne Dukes

June 1920.

THE UTILIZATION OF WASTE HEAT IN INTERNAL COMBUSTION ENGINES

Within the last few years the internal combustion engine has become quite prominent both in the engineering and manufacturing fields. The main advantages of the internal combustion engine over the steam engine are: its light weight, simplicity, quick starting, small bulk of fuel used, and fuel economy. It can be used where it would be impossible to use a steam engine or turbine.

In the internal combustion engine of today a great deal of heat is lost; part of this heat goes off in the exhaust, the remainder is carried away by the cooling water from the water jacket.

The idea carried out in my work was to use this "waste heat" to generate steam and to use this steam in the combustion cylinder alternately with the gas, in an endeavor to improve the thermal efficiency of the engine.

This idea was first conceived by Dean C. E. Ferris, who did some work in experimenting on the idea. In 1915 Mr. Roethe Weigel did some experimental work upon the same idea, using the same apparatus that was used in making the tests recorded in this work.

For the average internal combustion engine we may assume an efficiency of 21.3%. This leaves 78.7% of the heat that is lost in the exhaust, and by radiation through the cylinder walls. From various experiments we find that about 25.7% is carried off by the cooling water and 53% escapes in the exhaust gases. This represents a tremendous waste of energy, and if part of this energy could be utilized in some manner, it would add materially to the thermal efficiency of the engine.

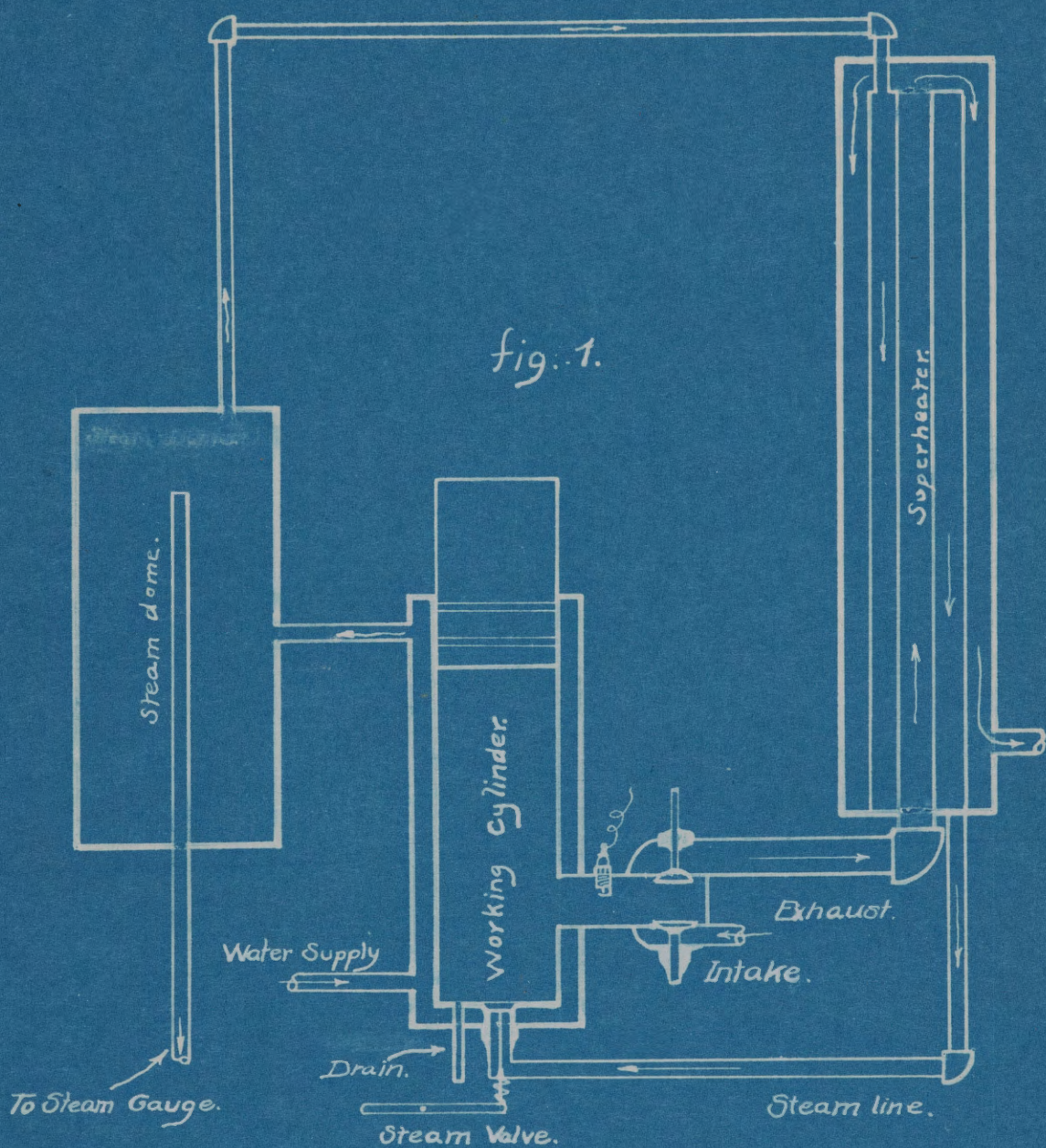
In experimenting work upon this idea, the water jacket of the engine was used as a boiler (see Fig. I), the steam being collected in a steam dome

especially provided for this purpose. The exhaust was used in a superheater to dry the steam as it leaves the steam dome, and just before it enters the working cylinder. This arrangement was used in the first test. A similar arrangement was used by Mr. Weigel in what he terms his second experiment. A good idea of this arrangement may be had by referring to page 8 of Mr. Weigel's thesis, where he gives two pictures, one showing the side view, and the other front view of the engine.

As the average steam engine has a thermal efficiency of about 8% and the waste heat of the gas engine is about 78.7%, the percent in efficiency that the internal combustion engine may be improved is $.787 \times .70 \times .08 = 4.4\%$; assuming the efficiency of the boiler to be 70%.

Since the efficiency of the engine was assumed to be 21.3%, the percent that the efficiency of the engine will be increased (by using steam) is 4.4 divided by 21.3 or 20.6 percent.

At the time I began work on the engine it was arranged as shown in Figure 1. The cam was arranged as shown in Figure 2. This cam actuates the steam valve, exhaust valve, and circuit closer. The valves operate as follows: at the beginning of the stroke all valves are closed with the piston in its lowest position; as the piston moves upward it creates a vacuum which actuates the suction valve (leading to the carburetter) admitting commercial gas and air in the correct proportions into the cylinder on the return stroke, the mixture of air and gas is compressed and just before the piston reaches lower dead center the electric circuit is closed by the mechanism as shown in Figure 2, and the mixture is then exploded by means of a spark plug, on the return stroke the gas is exhausted, just before the piston reaches lower dead center for the third time, the exhaust valve closes and the steam valve is opened, and steam is admitted on the return stroke, the steam is exhausted and



the engine is ready for the next cycle. By this arrangement we change the engine from a four cycle to a six cycle engine, using one working stroke of gas and one of steam for each cycle.

The first forty hours were spent in overhauling the engine. All valves had to be ground. The steam valve was very badly pitted, much trouble was experienced in grinding this valve as the whole head of the engine had to be removed. Because of the peculiar set-up of the engine this was a very difficult task. The valve seat was made of brass, while the valve was made of cast iron; when grinding the valve, the brass seat, which was not pitted would cut faster than the valve which was much harder and very badly pitted. The packing around this valve gave a great deal of trouble and had to be renewed several times.

The spring upon this valve was found to be too weak, and as a stronger spring was not obtainable, a weight was added to the valve to keep it closed. It is the opinion of the writer that this valve is too small as wire drawing was experienced in this test and in the two tests performed by Mr. Weigel in 1915.

A drain was installed to drain the combustion chamber should water or oil collect there. This drain was found to be very useful, especially when starting the engine for the first test, since both oil and water were found to leak into the combustion chamber, since the exhaust pipe was connected to a common exhaust pipe for several gas and gasoline engines, it is probable that oil has collected in this exhaust line and as this engine has not been run for several years, this oil gave a great deal of trouble, by leaking through the exhaust valve into the combustion chamber.

This drain was also found to be useful when first admitting steam, as there was always some water present, due to condensation. This last condition was bettered in the last experiment by placing a drain in the steam line.

just before it reaches the valve.

Considerable difficulty was experienced with the push rod and cam for this exhaust valve. This push rod was slightly too long, which caused the cam to bend it so badly during the first tryout that it would stick, holding the valve open. A new rod was made, but it was found to be short. It would not open the valve as wide as the old one did but, since the valve was extra large, it is doubtful if the operation of the engine was effected by the change. Much difficulty was experienced in keeping this rod from turning side ways and striking the cam gear wheel. Once just as I had raised enough steam pressure for a test, after running the engine for about three hours, the packing nut around the exhaust valve stem became loose and worked up vertically high enough to strike the push rod, causing it to turn and strike the cam gear and stick in such a position that it tore about a sixteenth of an inch off of each lobe of cam.

The entire engine had to be taken down to get to this cam. To take the engine down and repair and replace the cam took about twenty-four hours. It then took about six or eight hours to adjust the rod to prevent the recurrence of this accident. It is evidently in very good shape now, as it has never given any more trouble.

Considerable trouble was experienced with the governor, which is of the hit and miss type. It would hold the speed down too low for the design of the engine. This governor would allow the engine to fire two or three strokes and then it would hold the exhaust valve open, keeping the intake valve from operating, for two and sometimes three and four strokes before it would allow the exhaust valve to close, thereby allowing the engine to fire after the next intake stroke.

The governor was made up of two flyballs that actuated a lever arm. When

the speed increased beyond a certain limit, the pressure exerted by the fly-balls operated the lever arm in such a manner as to catch the exhaust valve stem, causing this valve to remain open.

The spring upon the fly-balls was provided with an adjusting screw. All adjustment possible was taken advantage of, but with very little success. Washers were then placed behind the adjusting screw, but the speed was increased but slightly, showing that the spring is either too weak or else the the fly-balls are too heavy.

The lever arm was then shortened several times; this gave slightly better results than the above, but still the speed was much below normal. The arm was shortened until while holding the exhaust valve over, the opening became so small that it allowed the suction to open the exhaust valve slightly allowing a lean mixture to enter into the cylinder, giving a slight explosion or pre-ignition which interfered with the operation of the engine. This was overcome in a measure, for the last length of the lever arm by tightening up on the intake valve spring, keeping it from opening until the exhaust valve was closed.

It is the opinion of the writer that both the intake and the fly-ball springs should be replaced. This was not done as they are special springs, and it is evident that they would have to be made to order. I believe that in order to get efficient operation of the engine, both of these springs should be replaced.

In the first test, with the arrangement described above, it took between two and three hours to obtain a steam pressure of 25 pounds per square inch boiler pressure. Upon admitting steam to the cylinder the pressure fell off rapidly to 15 pounds, the strength of the gas explosion fell off appreciably, almost stopping the engine. The speed then increased slowly until it was

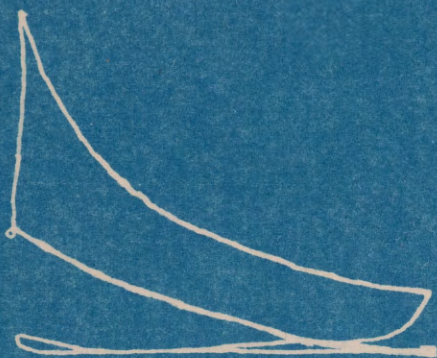
approximately the speed prior to the opening of the exhaust valve.

On page 9 will be found typical cards as taken in this test. Figure number 1 shows a card taken during a gas explosion, with a 60# spring in the indicator. At the time the card was taken it was carrying a load that held the speed so low that the governor did not interfere with the operation. Figure 2 shows a card that was taken immediately after the steam was admitted to the cylinder. It shows the effect of the steam on the explosion. Considerable less area is found in card number 2 than in figure 1. Figure 3 shows a card taken with an indicator using a 16 pound spring, and a collar to keep the pencil from going off of the card. This collar consisted of a number of brass washers placed upon the piston rod, inside of the spring of the indicator in such a manner as to shorten the stroke of the piston.

Figure No. 3 shows a card, taken before steam was admitted to the cylinder.

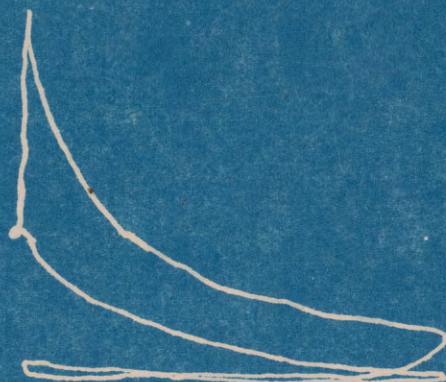
Figure No. 4 shows the first card that was taken after the steam was turned on.

From the appearances of these cards and the performance of the engine it was concluded that the superheating arrangement did very little toward drying the steam, the temperature of the gases entering the superheater was found to be only 312 degrees Fahr., and the temperature of the gases leaving the superheater was found to be 244 degrees Fahr., which gives an average of 256 degrees. According to Goodenough's steam tables, steam at 15 pounds pressure has a temperature of 213 degrees. This leaves a heat transfer of only $(256 - 213)$ 65 degrees, which is very small. In fact, I believe that more heat was lost in this arrangement than there would have been if the steam had been piped directly from the steam dome, because the superheating arrangement necessitated considerable external piping arrangement. Although all of the steam pipes were well covered with asbestos packing, there was much loss due



No. 1. 60th Spring. 150 R.R.N. No. 2. 60th Spring.

without Steam.



with Steam.



No. 3. 16th Spring.



No. 4. 16th Spring.

to radiation from these pipes.

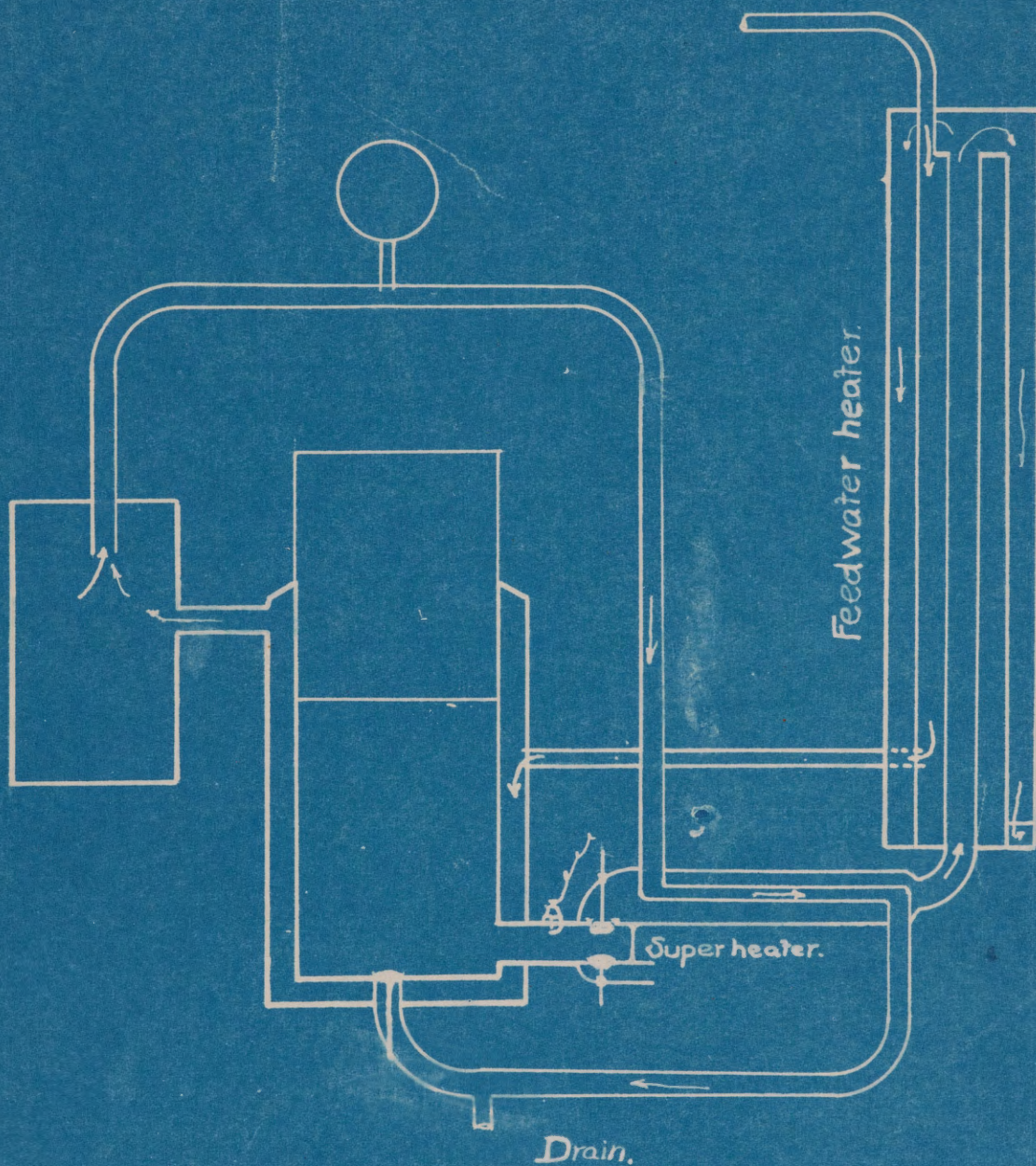
The superheater was entirely too large for its purpose. It would have worked much better had it been one-half the size, but this fact was not recognized in time to change it.

The steam did not bother the spark plug, as I secured just as good a spark after turning on the steam as I did before it was turned on. The trouble seemed to be due to the fact that the steam diluted the gas mixture, or else cooled the cylinder wall until the strength of the explosion was impaired, or else interfered with it in some other manner. It is possible that the pressure on the steam valve caused it to open slightly on the suction stroke, allowing some steam to enter and dilute the gas charge. If this is the condition, it could be overcome by putting a stronger spring upon this valve.

The author thinks that the increase of speed, while the engine was recovering after the admission of steam, as described above, is due to the fact that the pressure at the steam valve falls off much more rapidly than the pressure at the steam dome, due to wire drawing, radiation, and leakage.

In test number 2 the apparatus was arranged as in figure number 4, using the superheater as a feedwater heater, and the exhaust pipe leading to the feedwater heater as a superheater. This gives a superheater that is rather small, but it has the advantage of much higher temperature than the previous arrangement. A temperature of 313 degrees was obtained at the exit of this heater, giving a heat transfer of about 100 degrees. This arrangement has the advantage of preheating the water before it enters the boiler or water jacket. It is also better because it cuts down the length of steam pipe, thus cutting down radiation loss and leakage.

Figure number 1 was taken under some load, as in the first experiment



Arrangement used in Test No. 2.

and at the same speed it shows the gas explosion, with a 60-pound spring as before. Figure No. 2 shows card taken immediately after the steam was turned on. It shows practically the same conditions as found in the previous test. This card was found to be very near the same size as the card No. 2 of the previous experiment. Figure No. 3 shows a card that was taken with a 16-pound spring just before the steam was admitted. Figure No. 4 shows a card that was taken just after the steam was admitted. It shows little or no steam.

The gas explosion was affected as before, but to a less degree. This was probably due to the fact that less steam pressure was obtained. This also may explain why the arrangement used in this test did not show better results than the one used in test No. 1.

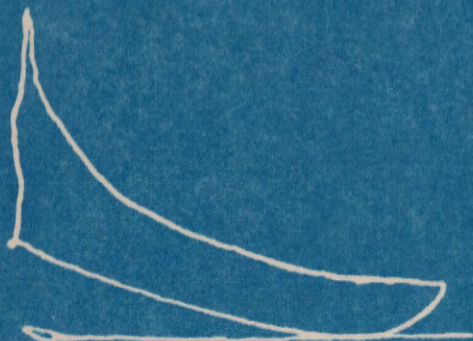
The writer believes that the superheater was too small to do any good, as the pipe carrying the steam through it was about ten inches long, and only a quarter of an inch in diameter.

THE STILL ENGINE

Reference may be made to the extract taken from the Journal of the Royal Society of Arts of June 6, which was published in the July (1919) number of the Mechanical Engineering magazine. The article reads as follows:

"The possibility of combining in one engine the superior thermal cycle at the higher temperatures and pressures of the combustion engine with the low thermal cycle of steam to deal with its rejected heat, and in the same engine to add the superior working advantages of the steam engine, is the basis of work carried out by Mr. W. J. Still."

The Still engine is an engine capable of using in its main working cylinder any form of liquid or gaseous fuel hitherto employed. It makes use of the recoverable heat which passes through the surfaces of the combustion



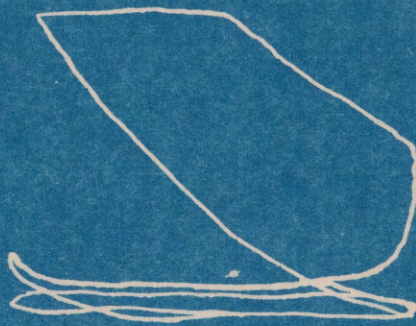
No. 1. 60th Spring.



No. 2. 60th Spring.



No. 3. 16th Spring.



No. 4. 16th Spring.

chamber, as well as into the exhaust gases, for the evaporation of steam, which steam is expanded in the combustion cylinder itself on one side of the main piston, the combustion stroke acting on the other side. It increases the power of the engine and reduces the consumption of the fuel per horsepower developed.

The primary object is not to use the waste heat for raising steam, but first to use it in improving the thermal conditions of the working cylinder, and so insure the maximum efficiency from the fuel burnt within it, diminishing as a consequence the heat lost in that operation. Since the maximum efficiency is obtained by combustion of the fuel in the cylinder, and the minimum by evaporation of the water in the steam generator, it is evident that the larger the quantity of steam which can be generated per horsepower developed by the combustion cycle, the lower must be the heat efficiency of the whole machine.

In the Still engine (see diagram) the jacket and cooling water form part of the circulating system of a steam generator, which may be an integral part of the engine or external to it. The cooling water therefore enters and leaves the jacket at a constant temperature, regulated by the pressure of the steam, the cooling being affected by converting the water into steam without raising its temperature. Excluding the radiation losses, which are kept low by lagging, all the heat which passes through the walls is thus usefully recovered in the water as steam. The temperature of the cylinder wall is uniform over the whole of its exterior surface, and the heat lost to the cooling water at each stage of the cycle--compression, combustion, and extension is diminished.

The exhaust gases after raising their quantum of steam are employed in preheating all the water required for the steam generated in the water jacket,

and the generator. Trials at full efficiency over long periods and steady loads show terminal tack temperatures as low as 150 degrees Fahr.

The quantity of steam capable of being generated from "waste heat" depends on the efficiency of the combustion cycle and the load. Some years of experimental work prove that the weight of steam recovered may attain a maximum of about 7 pounds per brake horsepower per hour developed by the combustion cycle of a four-stroke constant volume engine at full load.

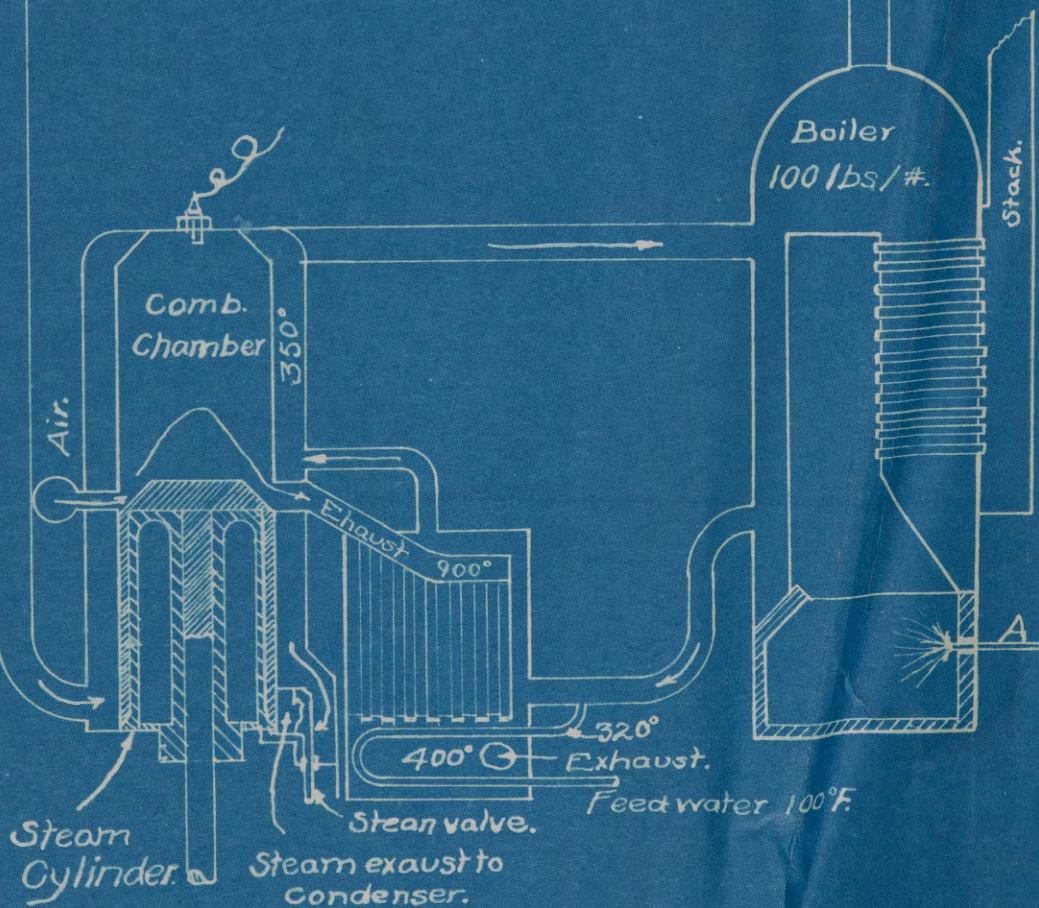
The first experimental engine constructed was a two-stroke engine capable of developing 590 boiler brake horsepower from three cylinders at 400 revolutions per minute and a bore of 8 inches. It was a high speed engine, designed with special regard to obtaining data about the recovery of steam from waste heat (jacket and exhaust). It was first operated on town gas--540 B. T. U. per cubic foot, and subsequently converted for oil fuel. Its efficiency was not high, owing to its being a two-stroke engine with a short stroke, but its consumption per brake horsepower was 15 cubic feet per hour (31.3 percent efficiency) a very promising result.

The outbreak of the war prevented much progress being made in the design and construction of gas engines; but the results achieved give great promise of future development, for with a combustion indicated efficiency of thirty-six percent, radiation four percent, boiler loss ten percent, there remains fifty percent for recovery. Allowing ten percent efficiency for the steam cycle a gain of five percent is assured, and the total indicated efficiency of the engine will not be less than 41 percent. If 20 percent efficiency is obtained from the steam cycle, as it appears possible, the total indicated efficiency will be about 46 percent.

A gas engine which can give a brake thermal efficiency 30 percent better than its predecessors, and which, by governor control alone, can meet any

Diagram Showing Arrangement
of Still Engine.

Fig. 3.



demand up to and over 100 percent overload, while maintaining a good efficiency at that increased output, cannot be neglected.

Four-stroke engines for coal oil and similar fuels have been built and tested ashore and afloat. A special $13\frac{1}{2}$ by 22 inch stroke cycle heavy oil engine with opposed pistons has been subjected to long and varied tests by representatives of various governments. The combustion takes place between the pistons, the steam acting on the return stroke at the back of each piston. The best consumption of fuel--Admiralty Shale Oil--was as low as 0.302 pounds per brake horsepower (scavenge pump not included) over a test of one hours duration. This engine will develop 330 brake horsepower at 380 revolutions per minute over short periods. (Combustion M.C.P. 128.2 pounds; steam M.C.P. 57.9 pounds; total M.C.P. 186.1 pounds).

The thermal brake efficiency from below quarter load to full power is maintained at approximately 40 percent over the whole range.

The application of the Still system to commercial marine work is being developed in this country and abroad, the two-stroke single piston type, in powers of 100 hp. per cylinder and 400 hp. per cylinder, 36 inch-cylinder giving 4200 shaft horsepower on two shafts with all auxiliaries and water would approximate 600 tons. A geared turbine in a similar ship would weigh 20 percent more and would consume approximately 2000 tons more fuel for a double journey lasting 1000 hours.

It has been conclusively proven in this work that steam can be generated by the proper use of the heat that is lost in the present-day internal combustion engine.

Mr. Still has proven that this steam can be generated in sufficient quantities that it can be made to do useful work. Although his method of using the steam was different, to the method employed here, he has proven what

we set out to prove, ie: that the waste heat of an internal combustion engine can be utilized to materially increase its thermal efficiency.

I attribute my failure to increase the efficiency of the engine used in this work to the fact that I was unable to get a boiler pressure high enough to insure dry steam at the entrance of the cylinder.

On the following page will be found an arrangement (for the engine described above) that is an improvement on the previous arrangement.

The principal changes are: a double coil in the feedwater heater, allowing the same heating surface, with a much shorter heater that will not effect the water level in the water jacket, a copper coil in the exhaust pipe for a superheater, and an arrangement marked A to keep any water from leaving the steam dome.

I believe that with this arrangement, coupled with a higher speed, mixture controlled, present-day model of gas or gasoline engine, that one could get a much higher pressure of steam, and that it would be much dryer than was obtained formerly.

Fig. 6.

