TWO DEVICES FOR IMPROVING THE THERMAL EFFICIENCY OF FIRED EQUIPMENT

W. P. MANNING and G. W. SAMS
C-E Natco Research and Development

COMBUSTION FUNDAMENTALS

It would be nice if elemental carbon and hydrogen could be burned and the entire heat of combustion could be obtained. But, handling raw elements is difficult, and hydrocarbons are by far the most available and convenient fuels. This means that the heat of formation of the hydrocarbon is lost. Fortunately, the heat of formation of fuel oils and natural gases is relatively small, e.g. 3 to 8 percent of the heat released.

Combustion of hydrocarbons is complicated by the fact that the water produced may or may not be considered to be condensed. This is the difference between the higher (water condensed) and lower (water not condensed) heating values (HHV and LHV). In calculations of thermal efficiency, the heat obtained by condensing the water vapor may or may not be considered to be available. This is the difference between the gross (heat available) and net (heat not available) thermal efficiencies (GTE and NTE). The HHV and NTE are the more widely used terms, simply because they are higher values. These terms are used throughout this paper even though the respective bases are inconsistent.

Figure 1 shows the NTE for burning natural gas (HHV of 1000 Btu/scf) in terms of the stack gas temperature and the excess air, which are the two parameters by which the performance of fired process equipment can be measured. The break in the curves at 100-130° F corresponds to the condensation of the water vapor produced during combustion. Above 135° F, the vapor pressure of water is greater than its partial pressure and condensation cannot occur. The NTE decreases with increasing stack gas temperature and the departure from linearity represents the change in the specific heat of the combustion gases with temperature. Below 135° F, the vapor pressure of the water vapor is less than the partial pressure and condensation occurs until it is essentially complete at 60° F. This corresponds to a GTE of 100 percent or a NTE of 111 percent. An efficiency over 100 percent means that heat is recovered which is not

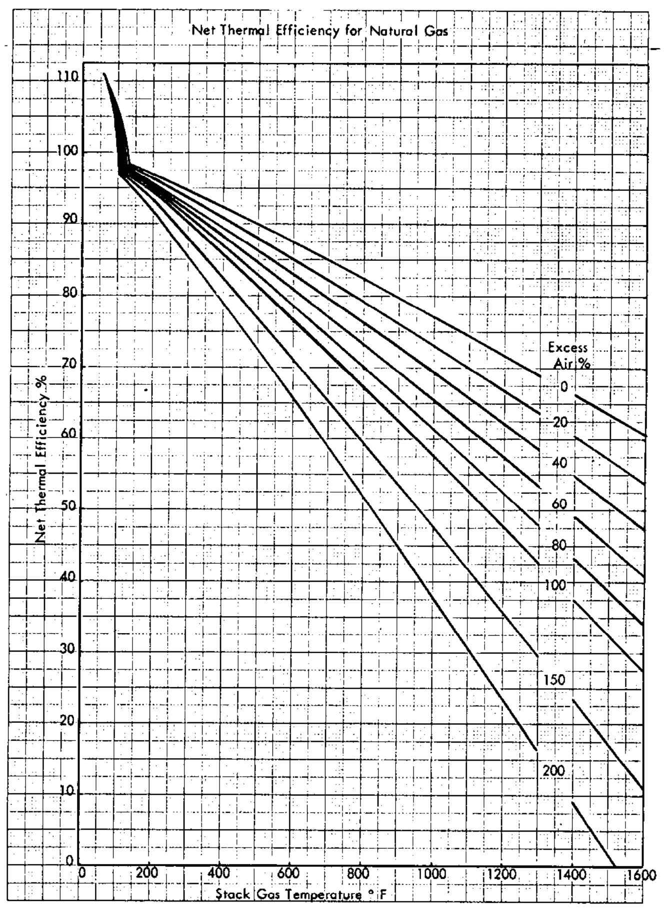


FIG. 1—NET THERMAL EFFICIENCY FOR NATURAL GAS

considered by the calculation procedure to be available.

The decrease in the NTE with increasing excess air is the result of increased sensible heat losses in the stack gases. About 10 percent excess air is needed for complete combustion of the fuel. Any additional air acts as a diluent. It reduces the flame temperature and the heat-transfer rate in the firetube and increases the amount of stack gases.

Methods for improving the NTE can be analyzed conveniently according to the function involved, that is, control of the excess air and recovery of more sensible heat from the stack gases.

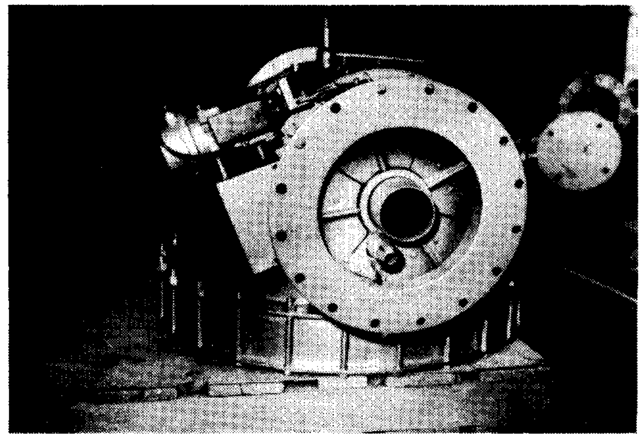
COMBUSTION AIR CONTROLLER

The significance of controlling the fuel-air ratio is shown in Figure 1. For an indirect-fired, water-bath heater with the stack gas at 1000^0 F, the NTE drops 0.2 percent for every 1 percent increment in excess air. Currently, the firetube and stack are usually designed to provide 20 percent excess air at high fire. At low fire the stack gas temperature and the resulting stack draft do not decrease sufficiently to prevent operation far above 20 percent excess air. And when the main burner is shut off, leaving only the pilot on (no-fire condition), the stack draft continues to cool the heater. When the main burner relights, the heat which has been lost must be replenished before the heater can operate at maximum capacity.

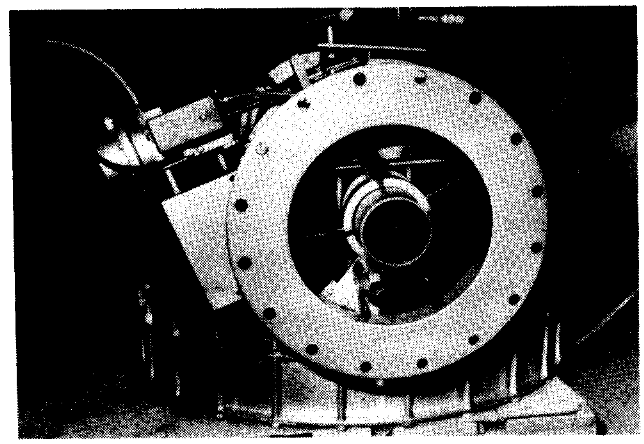
On some heaters, (All design and design features are from CE-Natco unless otherwise noted.) the air flow at high fire is controlled by adjustment of a damper located around the burner at the inlet to the firetube. The position of the damper remains fixed and the purpose is to compensate for changes in stack draft due to location altitude, burner orifice size, operating gas pressure at the burner, etc.

Figure 2 shows the design of a combustion air controller. The major component is a damper which consists of several annular sections or vanes that rotate around radial lines from the center of the burner. The vanes interlock and are assembled in a spool which is inserted between the flame arrestor and the firetube flange. The burner and pilot are mounted in a stationary plate.

The vanes are capable of a full 90-degree rotation, i.e. from completely closed to wide open. The positions of all vanes are controlled simultaneously



CONTROLLER WITH VANES CLOSED



CONTROLLER WITH VANES OPENED

FIG. 2—COMBUSTION AIR CONTROLLER

by linkages installed around the spool. In turn, movement of the linkage is controlled by a piston-type actuator. By application of the same pneumatic signal simultaneously to the actuator and the fuel-gas control valve, the excess air can be controlled over the entire firing range. Both the actuator and the fuel valve fail closed. The demand for heat ignites the main burner and the magnitude of the control signal determines the firing rate.

FIRETUBE ECONOMIZER

Figure 1 also shows the effect of reducing the stack gas temperature. At 20 percent excess air the NTE increases 3 percent for every 100° F decrease in the stack gas temperature. The effect is greater if the excess air is increased.

Several designs have been suggested for recovering sensible heat from the combustion gases. In all of the designs a coolant such as the water bath of an indirect heater is pumped through finned pipes which are installed in the stack gases. Safety requires that shut down occur when the flow of coolant fails. Usually the cost of such an economizer is prohibitively high.

It is possible to cool the stack gases without pumping coolant through an exchanger and Figure 3 shows the design of a firetube economizer. The heat transfer is accomplished in the firetube itself, where helically finned pipes are installed vertically in the last few feet. Expansion or even partial vaporization of the water in the pipes promotes an upward flow which removes the heat transferred from the firetube gases. The system is completely automatic. When the main burner is lit and the firetube gases are hot, the water in the pipes heats up and rises; and when the burner is extinguished the pipes cool and the water flow subsides. Note that the decrease in the stack draft produced by the lower stack gas temperature can be offset by increasing the height of the stack.

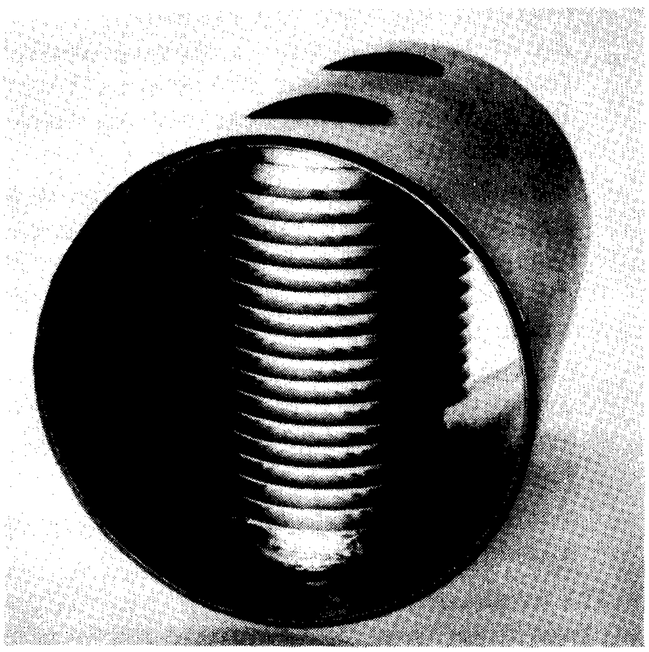


FIG. 3—FIRETUBE ECONOMIZER

TEST EQUIPMENT

The performance of the combustion air controller and the firetube economizer was evaluated using an indirect fired, water bath heater. Figure 4 shows the principal components and the general arrangement. Key dimensions of the heater are those for the shell (3 ft OD by 10 ft long), the firetube (10 in. OD with

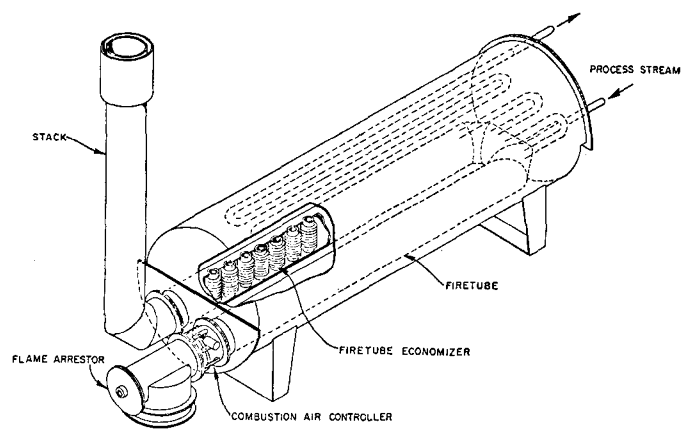


FIG. 4—TEST HEATER

52 sq ft surface area) and the stack (10 in. ID by 11 ft high).

Firing equipment included a Tee-type flame arrestor, a 3-inch Eclipse burner, and a C-E Invalco RHSB pilot. The combustion air controller was mounted between the firetube and the flame arrestor. The design was four louvers on a 4-inch OD burner ring in a 10-inch ID spool.

An extra firetube containing a firetube economizer was constructed. The economizer section consists of one row of seven 3-inch Sch. 40 pipes. The finning is 24 fins/foot, 3/4 inch high and 0.105 inch thick. The internal (combustion side) surface area of the firetube with the economizer is 72 square feet. This firetube allowed the test heater to be assembled in the different configurations needed to measure the effect of the combustion air controller and the firetube economizer individually and collectively.

A coil bundle was installed in the test heater to remove the heat released by the burner. It is a one flow path, 14 pass, 2 inch Sch. 80 pipe arrangement. Thermometers were installed in the inlet and outlet lines. The flow rate of the water used to simulate the process stream was measured with a Rockwell vane meter. The water-bath temperature was measured with a thermometer. The stack-gas temperature was monitored with a dial thermometer. Accurate measurements were obtained with an iron-constantan thermocouple and a millivolt potentiometer.

The fuel gas piping is shown in Figure 5. The line to the main burner contains a 1 inch Fisher 630 regulator, a Rockwell positive displacement gas meter, a C-E Invalco DSG-7501 control valve, and an isolation valve. The pilot line contains a Fisher Y-200 regulator and a 1/4 inch needle valve. Except for the gas meter, the above components are standard equipment for a 0.75 MM Btu/hr heater as are the Eclipse burner and the RHSB pilot.

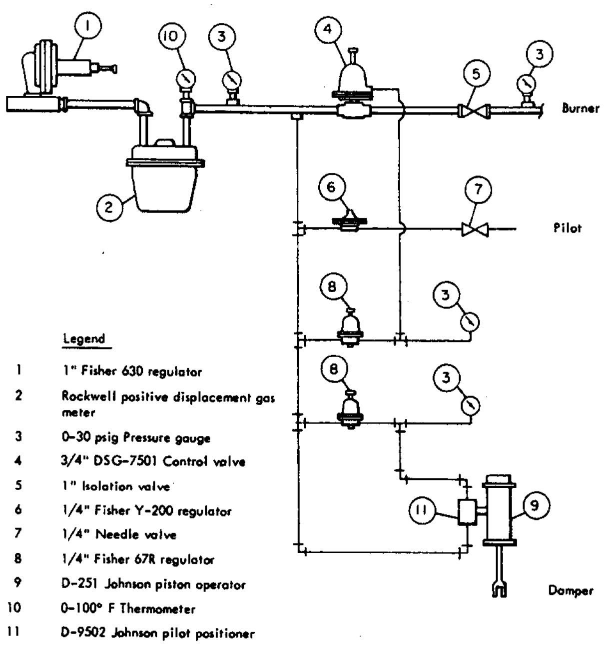


FIG. 5—FUEL GAS PIPING

A Fisher 67R regulator was used to supply an adjustable control signal of 3 to 15 psig to the actuator and the DSG-7501 control valve. The firing rate is therefore independent of both the water-bath temperature and the process stream. This is a desirable departure from the usual temperature-control system, and it is a convenient way to obtain the constant fuel-gas and combustion-air flow rates needed for test runs. Three pressure gauges and a thermometer completed the instrumentation.

The stack gas composition was obtained from a small sample stream which was removed continuously from the stack by means of an aspirator. The sample was passed through a water-cooled heat exchanger to condense the water. The oxygen content was read continuously with a Beckman analyzer, and the results checked with a gas chromatograph.

RESULTS

The thermal efficiency of the test heater was determined over the entire firing range for four different configurations. These conditions are as follows.

The heater without the combustion air controller and firetube economizer.

The heater with the combustion air controller.

The heater with the firetube economizer.

The heater with both the combustion air controller and firetube economizer.

The following test procedure was used for all of the configurations.

Light the pilot and the main burner, and bring the heater bath up to the desired operating temperature of 180-195° F.

Adjust the Fisher 67R regulator to give the desired pneumatic signal to the diaphragm actuator for the damper and the fuel-gas control valve. This is simply setting the firing rate.

Adjust the water-flow rate in the process coil to keep the water in heater shell between 180 and 195° F. Wait about one hour to obtain steady-state conditions.

Record the fuel-gas flow rate, the process-stream water-flow rate and temperature change, the water bath temperature, the fuel gas pressure at the burner, and the stack-gas temperature and oxygen content.

Calculate the percent excess air from the oxygen content and the NTE from the stack gas temperature and the percent excess air using Figure 1.

Confirm the validity of the above data by making a heat balance on the heater.

The results are shown in Figure 6. The NTE for the basic heater varies from 47 percent at low fire to 69 percent at high fire where the stack gases are at 1100° F and the excess air is 20 percent. Corresponding values for low fire are 700° F and 250 percent. So the poor efficiency at low fire is the result of excessive stack drafting.

Installing the combustion air controller maintains the excess air at 15-25 percent over the entire firing range. The NTE then depends on the stack gas temperature which varies from 800° F at low fire to 1100° F at high fire. The corresponding NTE's are 77

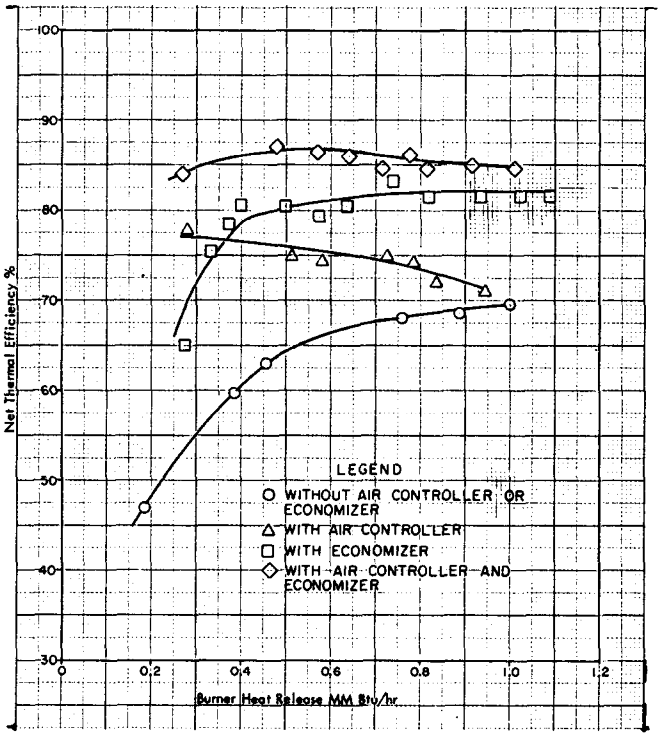


FIG. 6—PERFORMANCE DATA

percent and 71 percent.

The NTE with the firetube economizer ranges from 65 percent at low fire to 81 percent at high fire. The improvement in the NTE over that for the basic heater is the result of lower stack gas temperatures which are 430° F at low fire and 800° F at high fire. However, the excess air is undesirably high at low fire.

Together the combustion air controller and the firetube economizer raise the NTE to approximately 85 percent over the entire firing range. This is a 15-percent increase at high fire and a 35-percent increase at low fire. The excess air ranges from 15 to 25 percent and the stack gas temperature from 400 to 700° F.

FIRETUBE AND STACK DESIGN

While the improvement in the NTE is the most significant part of the current investigation, more information is needed to design the firetubes and stacks. This includes detailed measurements of the temperature profiles and pressure drops along the firetube. Though not included in this paper, the pertinent information has been obtained and used to develop correlations for the rate of heat transfer across the firetube wall and the gas pressure drop across the finned tubes. These correlations provide the background for a computer program to design firetubes and stacks.

The CDC 7600 program builds the firetube in 1-

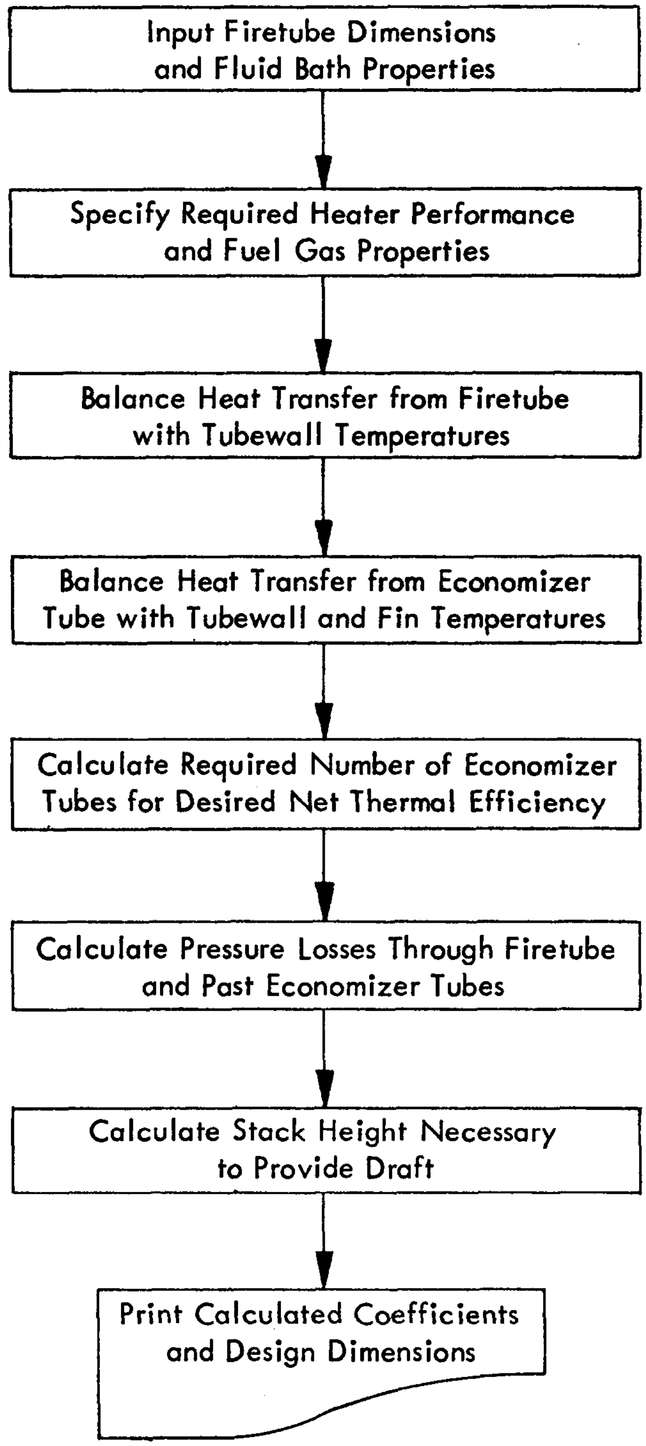


FIG. 7—FLOW SCHEME FOR COMPUTER ANALYSIS

foot increments, starting with the maximum combustion-gas temperature at the burner. Economizer tubes are inserted in the return leg when the flue gases have cooled sufficiently to avoid excessive fin-tip temperatures. The program continues until the stipulated thermal efficiency is obtained. An examination of the pressure drop in the firetube and the stack height needed to provide sufficient draft completes the analysis. The flow scheme for this computer program is given in Figure 7.

The above design procedure has been applied to all fire equipment produced by C-E Natco. Standard economizer tube and stack designs are available from 0.25 to 5.0 MM Btu/hr. The corresponding firetube diameters range from 8 to 24 inches. The combustion air controller is available as an integral part of the firetube and flame-arrestor assembly.

The improved thermal efficiency results in a substantial fuel savings for an operating year. An increase in the NTE from 69 to 84 percent reduces the fuel consumption by 24 percent. For a 1 MM Btu/hr heater the annual operating cost is reduced from $14,810 to $11,230, based on a fuel cost of $1/Mscf and an operating year of 8600 hours. Based on the combined selling price of the air controller and economizer, the payout period is less than one year for heater sizes from 0.5 to 5 MM Btu/hr.