NBSIR 84-2925

Prediction of Performance for a Fire-Tube Boiler With and Without Turbulators

David A. Didion
Lih Chern

U.S. DEPARTMENT OF COMMERCE
National Bureau of Standards
Center for Building Technology
Building Equipment Division
Gaithersburg, Maryland 20899

July 1984

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U.S. DEPARTMENT OF COMMERCE, Malcolm Baldrige, *Secretary*
NATIONAL BUREAU OF STANDARDS, Ernest Ambler, *Director*

ABSTRACT

A series of computer runs were made using DEPAB2 (the boiler simulation computer program). They include the runs for a fire-tube boiler 'as-is' (i.e., without turbulators), with wire-coil type turbulators, and with twisted-tape type turbulators, respectively. Output from these runs are used to evaluate the boiler seasonal performance values under the Washington, D.C. weather conditions. Results show that the turbulator increases the boiler seasonal efficiency from 2.87 to 6.08%.

Key Words: Boiler performance; boiler simulation; enhanced heat transfer; fire tube boilers; turbulators.

DISCLAIMER

In view of the presently accepted practice of the building industry in the United States and the structure of the computer software used in this project, common U.S. units of measurement have been used in this report. In recognition of the United States as a signatory to the General Conference of Weights and Measures, which gave official status to the SI system of units in 1960, appropriate conversion factors are provided below for the units used in this report.

Temperature	F = 9/5 C + 32
Energy	1 Btu = 1.05506 kilojoules (kJ)

ACKNOWLEDGMENTS

Thanks to Dr. Joseph Chi of HCP Systems for his invaluable technical assistance and review, and to Mr. James Thompson of USAFESA for his administrative guidance. Also thanks to Dr. A. Bergles of Iowa State University for supplying the required input data on forced convection heat transfer coefficients.

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1. INTRODUCTION

This report describes an investigation on effects of inserts for the boiler tubes on the performance of the fire-tube boiler. A series of runs for a typical fire-tube boiler with and without turbulators were made using DEPAB2 [1] and the effect of turbulators on its performance is evaluated employing the on/off and fuel/air metering controllers. Also, performance comparisons on an annual basis are made of the fire-tube boiler with and without turbulators.

2. TYPES OF CONTROLLERS

The on/off controller senses the boiler output temperature. Fuel/air supply turns on when the boiler temperature drops below a lower preset value, and turns off when the temperature rises above a higher preset value.

The fuel/air metering controller has a primary feedback element sensing the boiler temperature. The output signal from the feedback element is combined with the setpoint signal and processed by the fuel/air flow metering controller. The resultant actuating signal from the fuel/air automatic controller is used to position the burner control elements to adjust fuel/air flow in proportion to load. There is usually a minimum firing rate for a boiler burner, so a boiler with an fuel/air metering controller operates in an on/off mode when heating load is smaller than the boiler steady-state output at its minimum firing rate.

Curves of steady-state air and fuel flow rates versus the boiler temperature are shown in figure 1.

3. HEATING LOAD

The boiler heating load is assumed to be proportional to the temperature difference of 70°F minus the outdoor air temperature. Two heating load curves have been used. One is that the boiler is at full load at the design outdoor temperature of 10°F for Washington, D.C. Another is that the boiler is at half load at the design outdoor temperature of 10°F. These curves are shown in figure 2. Figure 3 shows the typical weather at Washington, D.C. during a heating season.

4. RESULTS AND DISCUSSIONS

Results of runs for a typical boiler for the cases of with and without turbulators are summarized in figures 4 and 5, where the fuel utilization efficiency values are plotted versus outdoor air temperatures. The seasonal efficiencies under weather conditions described above are plotted in figure 6.

The amount of reduction in fuel consumption by inserting tabulators into the last pass of the boiler tubes is shown in the following table.

Controller Type	Turbulator Type	Load Condition	Reduction in Fuel Consumption
On/Off	Wire Coil	Full 10F	6.1
On/Off	Twist Tape	Full 10F	4.0
Metering	Wire Coil	Full 10F	5.2
Metering	Twist Tape	Full 10F	3.5
On/Off	Wire Coil	Half 10F	6.0
On/Off	Twist Tape	Half 10F	3.8
Metering	Wire Coil	Half 10F	4.3
Metering	Twist Tape	Half 10F	2.9

In this table the reduction value is calculated by the equation:

$$\text{Reduction in Fuel Consumption (\%)} = \frac{Q_o - Q_w}{Q_o}$$

$$= \frac{\frac{1}{\eta_o} - \frac{1}{\eta_w}}{\frac{1}{\eta_o}} \times 100$$

where Q_o = fuel consumption without turbulator

Q_w = fuel consumption with turbulator

η_o = seasonal efficiency without turbulator

η_w = seasonal efficienty with turbulator

It can be seen in figure 4 that for a boiler with an on/off controller, fuel utilization efficiency values decrease as the outdoor temperature rises and that for a boiler with a metering controller fuel utilization efficiency values first rise with the outdoor temperature and then, at temperatures above 45°F, drops with further rising in the outdoor air temperature. The latter can be explained as follows: When the heating load is smaller than the boiler steady-state output at its minimum firing rate, the boiler (with metering controller) will operate in an on/off mode with 'on' being at the lowest firing rate. In this case, the efficiency will decrease as heating load drops. When heating load is larger than the boiler steady-state output at its minimum firing rate, the firing rate is directly proportional to the heating load. Since lowering of the firing rate is accompanied by increasing the gas residence time, the boiler efficiency increases as the firing rate decreases (as the outdoor air temperatures increases).

For runs with turbulators discussed in this report, their lengths are all at 3/5th of the pipe length of the last pass. Heat transfer data for the fire tubes with the turbulators are correlated by the following equations [2]:

$$Nu = 0.515(Re)^{0.584}(Pr)^{0.4} \quad \text{(with wire coil turbulators)}$$

$$Nu = 0.200(Re)^{0.640}(Pr)^{0.4} \quad \text{(with twisted tape turbulators)}$$

where Nu, Re, Pr are Nusselt, Reynolds and Prandtl numbers, respectively [3].

Calculation of the boiler seasonal performance values from the DEPAB2 output values are listed in twelve tables which are appended to this report.

5. CONCLUSIONS

The simulation analysis results may appear somewhat disappointing from an improvement in energy performance viewpoint. Also, they may seem contradictory to the rather significant improvement in heat transfer performance brought about by the insertion of the various turbulators (100+% [2]). However, it should be realized that the majority of heat transfer occurs in the fire box region where both radiation and convection exist and that the longer the gases travel in the tubes, the more the heat transfer decreases due to decreasing gas temperature. Thus, since the simulation considered that the insertion of the turbulators was limited to only 60% of the final pass of the fire tubes (due to practical limitations). even the potential for overall boiler performance improvement is quite diminished.

On the other hand, a continual decrease in exhaust gas temperature will result in a release of acidic condensate which must be avoided in boilers not specifically designed to handle such a corrosive liquid. The exhaust gas temperatures at which this condensation limitation occurs are such that it is not theoretically possible to improve the boiler's efficiency past 88%. Relative to this boiler efficiency performance cap the wire coil turbulator (Table 2 of Appendix) appears to be improving the performance to the limit.

Although different control schemes and part load performance was considered to a limited degree in this simulation, the effect of scale build-up due to particulates, etc. was not considered. Therefore, the absolute values of the performance figures listed in the appendix tables are probably greater by a few percent than what can be expected from actual boiler performance.

6. REFERENCES

[1] Chi, J., Chern, L., and Didion, D., "A Commercial Heating Boiler Transient Analysis Simulation Model (DEPAB2)", NBSIR 83-2638 to U.S. Army Facilities Engineering Support Agency, January 1983.

[2] Junkhan, G.H., Bergles, A.E., Nirmalan, Ravigururajan, T., "Tests of Turbulators for Fire Tube Boilers", Iowa State University Report to U.S. Army Facilities Engineering Support Agency, December 1982.

[3] ASHRAE Handbook 1981 Fundamentals, Chapter 2.

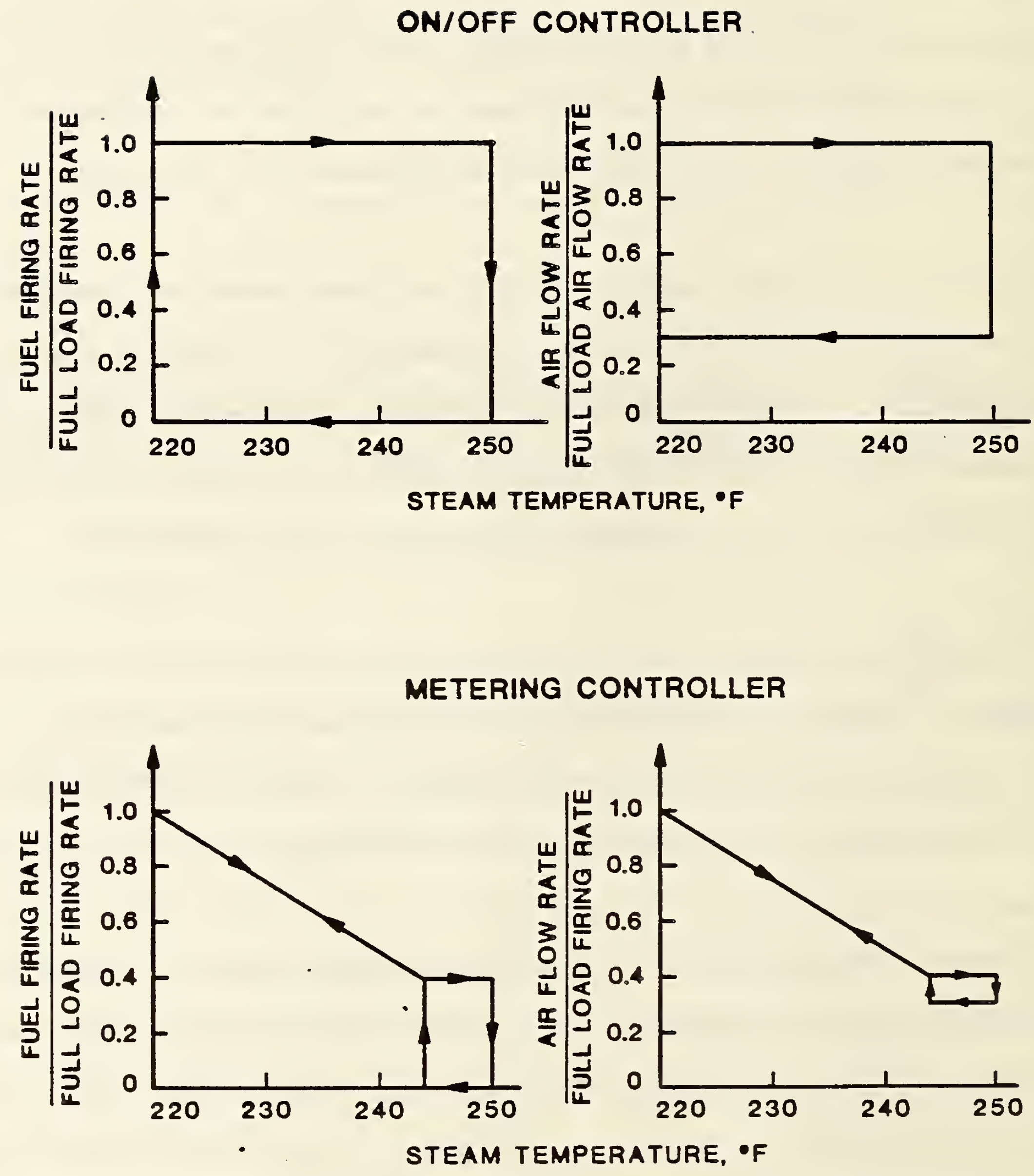

Figure 1. Logic for on/off controller and metering controller.

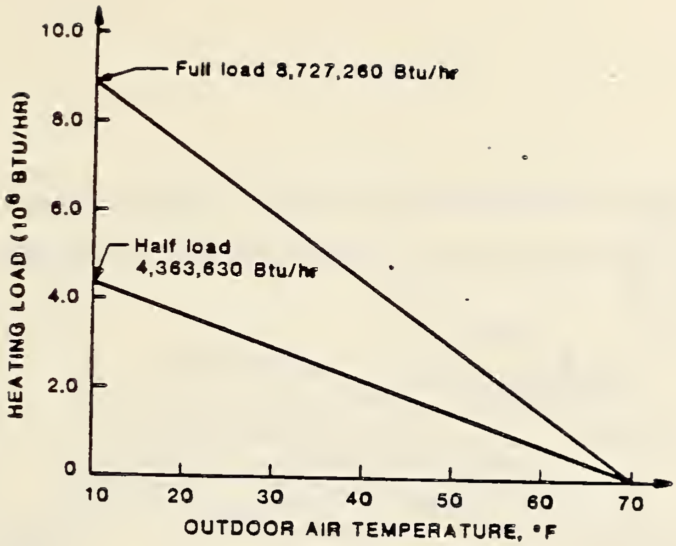

Figure 2. Heating load curve.

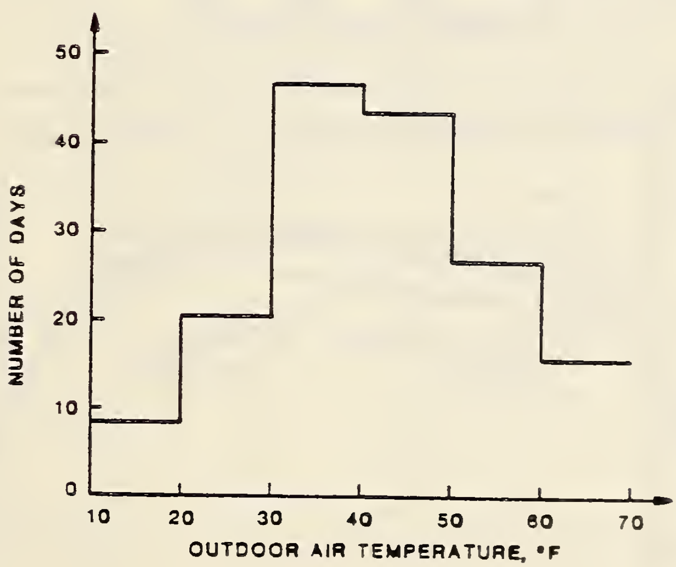

Figure 3. Typical weather at Washington, D.C. during the heating season.

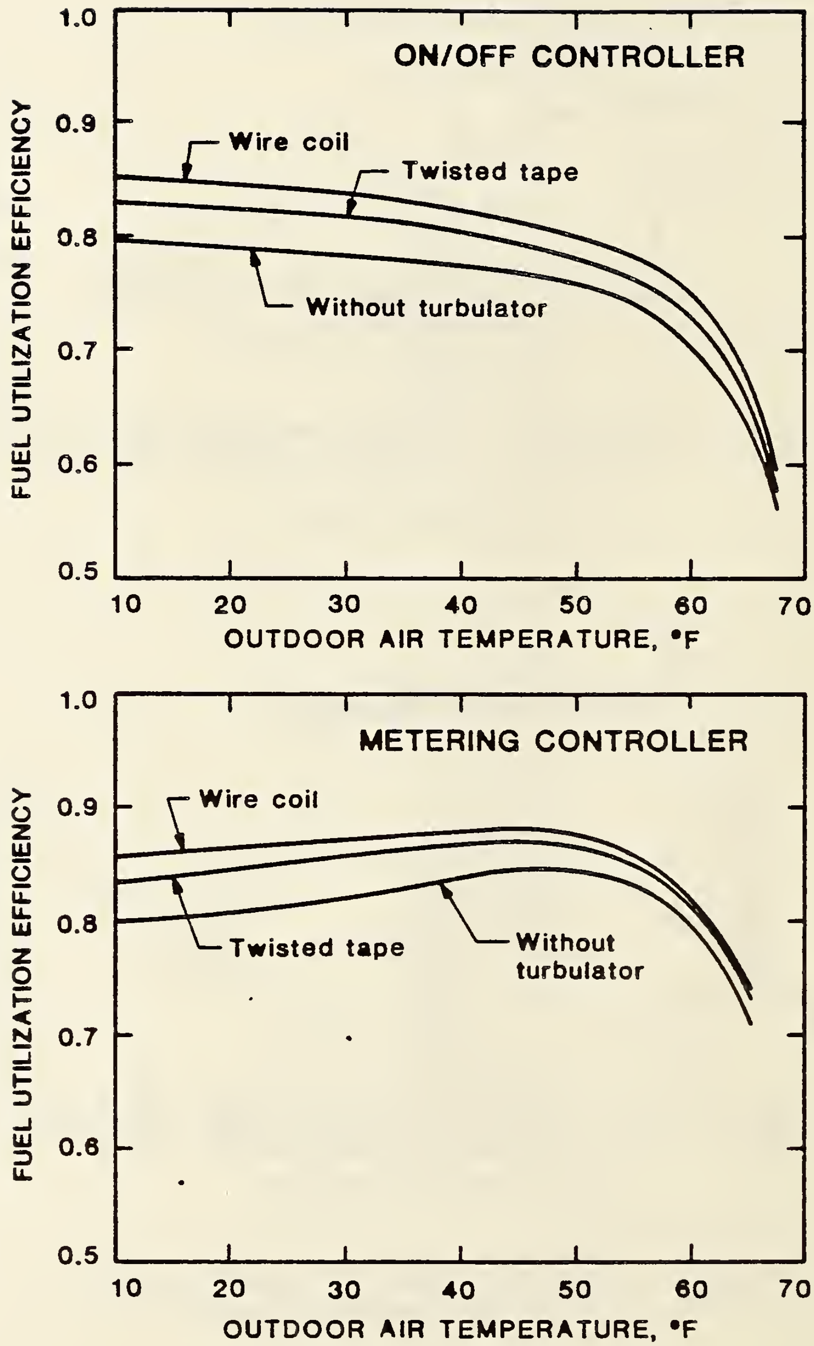

Figure 4. Fuel utilization efficiency versus outdoor temperature, full load at 10°F.

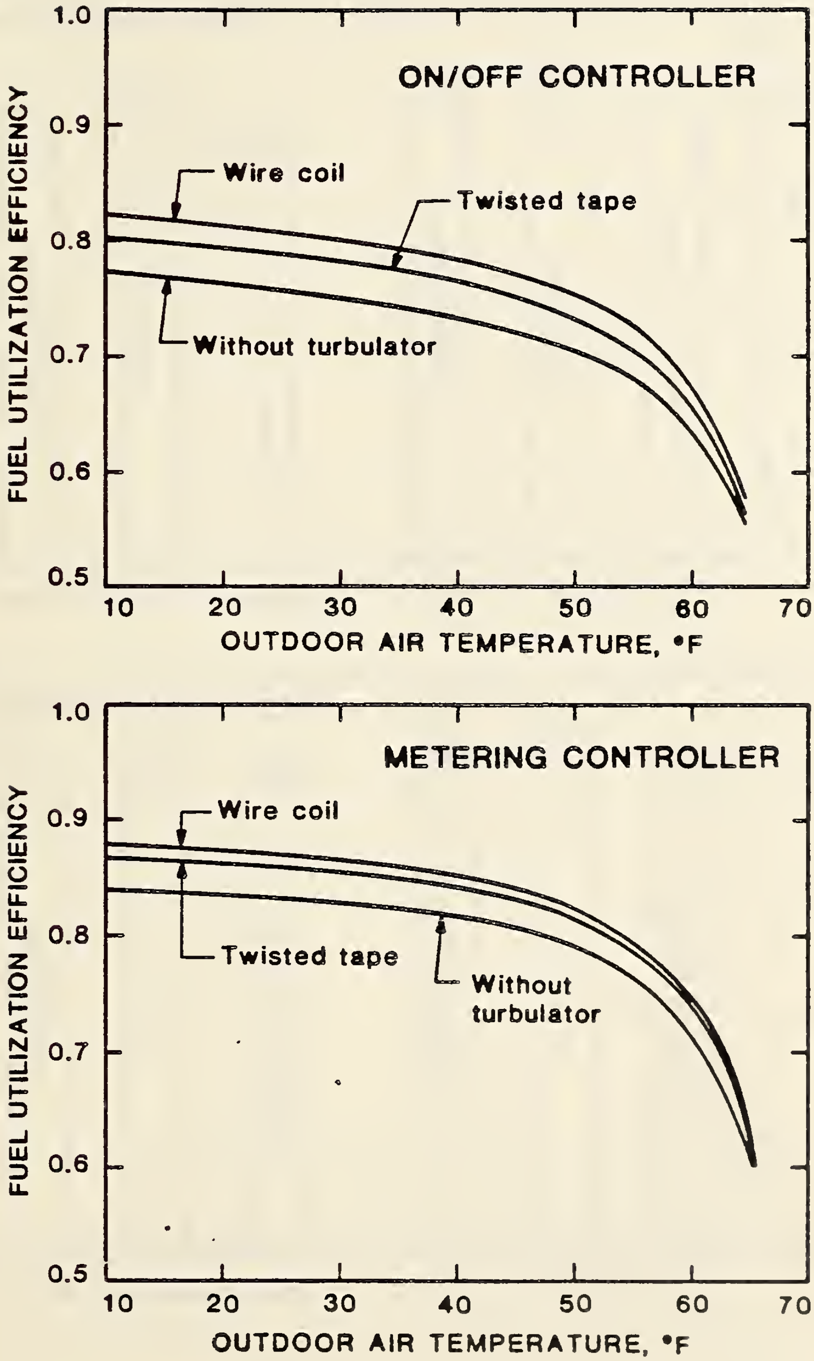

Figure 5. Fuel utilization efficiency versus outdoor temperature, half load at 10°F.

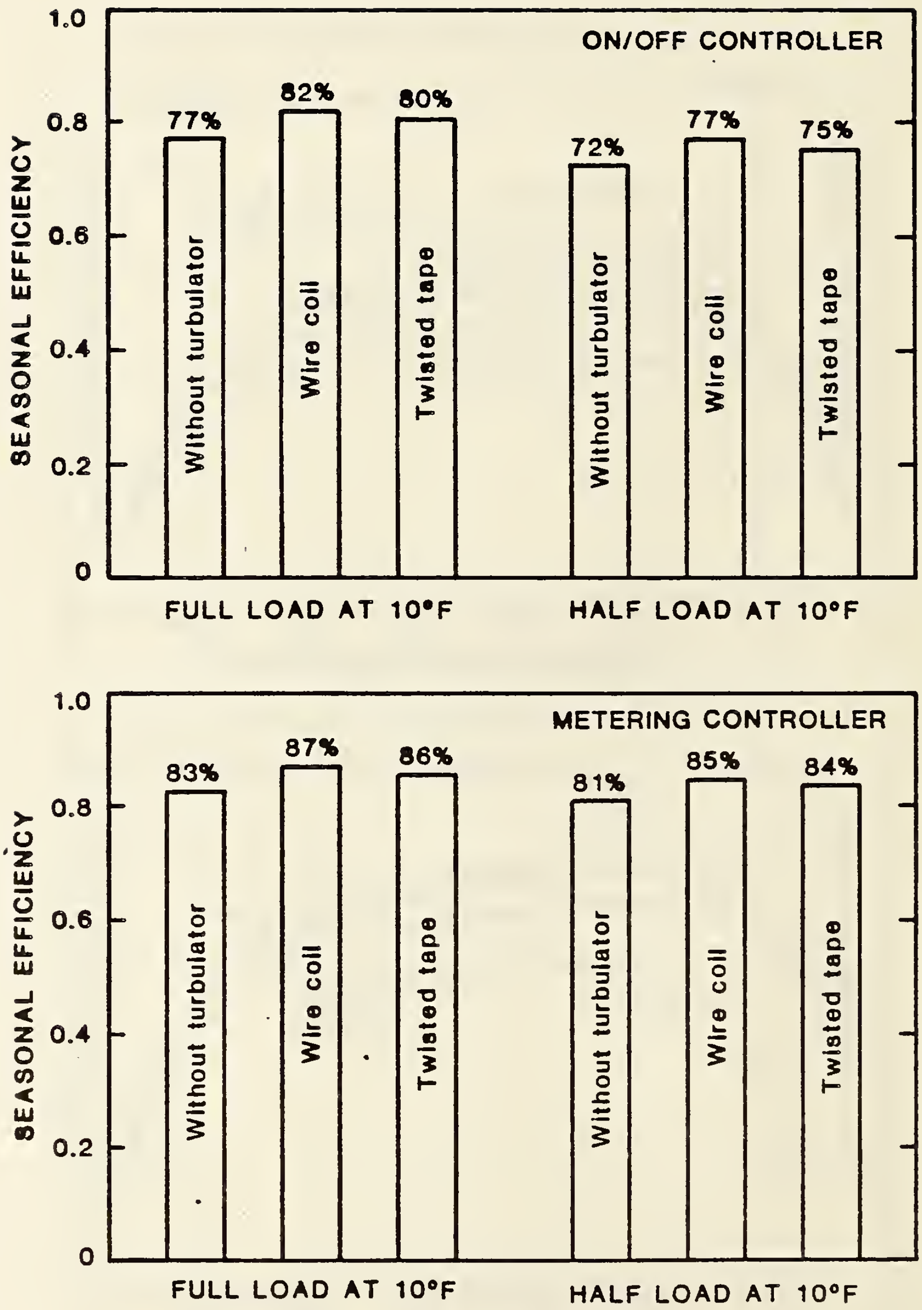

Figure 6. Seasonal efficiency.

APPENDIX

DETAILS OF SEASONAL PERFORMANCE CALCULATIONS

LIST OF TABLES

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	195.7	243.6	1634.095	2034.06
25	20.33	161.8	198.4	3289.394	4033.472
35	46.65	127.1	153.3	5929.215	7151.445
45	43.39	91.7	108.3	3978.863	4699.137
55	26.69	55.2	66.4	1473.288	1772.216
65	15.43	18.5	25.9	285.455	399.637
TOTAL LOAD (10^6 BTU/YEAR) 16590.3					
TOTAL FUEL (10^6 BTU/YEAR) 20090.0					
ANNUAL EFFICIENCY (PERCENT) 82.6					

Table 1. Pipe Without Turbulator (Metering Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	196.4	227.9	1639.94	1902.365
25	20.33	162.2	186.5	3727.526	3731.545
35	46.65	127.3	145.0	5938.545	6764.25
45	43.39	92.2	104.7	4000.558	4542.933
55	26.69	55.2	64.3	1473.288	1716.167
65	15.43	18.5	24.8	285.455	382.664
TOTAL LOAD (10^6 BTU/YEAR) 16635.312					
TOTAL FUEL (10^6 BTU/YEAR) 19100.524					
ANNUAL EFFICIENCY (PERCENT) 87.1					

Table 2. Pipe With Wire Coil (Metering Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	196.1	233.5	1637.435	1949.725
25	20.33	162.0	190.7	3293.46	3876.931
35	46.65	127.3	147.8	5938.545	6894.87
45	43.39	91.8	104.9	3983.202	4551.611
55	26.69	55.2	65.3	1473.288	1742.857
65	15.43	18.5	25.1	285.455	387.293
TOTAL LOAD (10^6 BTU/YEAR) 16611.385					
TOTAL FUEL (10^6 BTU/YEAR) 19403.28					
ANNUAL EFFICIENCY (PERCENT) 85.6					

Table 3. Pipe With Twisted Tape (Metering Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	199.65	251.34	1667.1	2098.7
25	20.33	163.81	207.75	3330.2	4223.5
35	46.65	127.8	164.29	5962.5	7664.1
45	43.39	91.61	120.53	3874.9	5229.9
55	26.69	55.2	75.37	1473.3	2011.7
65	15.43	18.5	28.99	285.5	447.3
TOTAL LOAD (10^6 BTU/YEAR)	16693.5				
TOTAL FUEL (10^6 BTU/YEAR)	21675.2				
ANNUAL EFFICIENCY (PERCENT)	77.0				

Table 4. Pipe Without Turbulator (On/Off Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	199.71	235.12	1667.6	1963.3
25	20.33	163.85	194.67	3331.1	3857.6
35	46.65	127.89	154.9	5966.2	7225.8
45	43.39	91.68	113.08	3977.9	4906.4
55	26.69	55.24	70.8	1474.2	1889.7
65	15.43	18.51	27.46	285.6	423.8
TOTAL LOAD (10^6 BTU/YEAR)	16702.6				
TOTAL FUEL (10^6 BTU/YEAR)	20366.6				
ANNUAL EFFICIENCY (PERCENT)	82.0				

Table 5. Pipe with Wire Coil (On/Off Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	199.63	241.45	1666.9	2016.1
25	20.33	163.85	199.6	3331.0	4057.9
35	46.65	127.87	157.82	5965.2	7362.2
45	43.39	91.65	115.7	3976.7	5018.6
55	26.69	55.21	72.49	1473.6	1934.7
65	15.43	18.5	28.04	285.6	432.7
TOTAL LOAD (10^6 BTU/YEAR)	16699				
TOTAL FUEL (10^6 BTU/YEAR)	20823.2				
ANNUAL EFFICIENCY (PERCENT)	80.2				

Table 6. Pipe with Twisted Tape (On/Off Controller) Full Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	99.912	119.49	834.3	997.79
25	20.33	87.0	104.69	1768.7	2128.3
35	46.65	63.99	77.72	2985.13	3625.55
45	43.39	45.80	56.76	1987.11	2462.8
55	26.69	27.54	36.01	735.04	961.14
65	15.43	9.203	15.12	142.0	233.28
TOTAL LOAD (10^6 BTU/YEAR)		8452.3			
TOTAL FUEL (10^6 BTU/YEAR)		10408.9			
ANNUAL EFFICIENCY (PERCENT)		81.2			

Table 7. Pipe Without Turbulator (Metering Controller) Half Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	100.08	113.78	835.67	950.0
25	20.33	82.19	94.16	1671.0	1914.4
35	46.65	64.00	74.35	2985.6	3468.56
45	43.39	45.8	54.48	1987.5	2363.94
55	26.69	27.54	34.7	735.16	926.27
65	15.43	9.203	14.74	142.0	227.5
TOTAL LOAD (10^6 BTU/YEAR)		8356.9			
TOTAL FUEL (10^6 BTU/YEAR)		9850.7			
ANNUAL EFFICIENCY (PERCENT)		84.8			

Table 8. Pipe With Wire Coil (Metering Controller) Half Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	100.03	115.63	835.27	965.53
25	20.33	82.23	95.61	1671.68	1943.85
35	46.65	65.99	75.52	3078.43	3522.97
45	43.39	45.8	55.23	1987.25	2396.42
55	26.69	27.54	35.12	734.94	937.35
65	15.43	9.204	14.87	142.02	229.4
TOTAL LOAD (10^6 BTU/YEAR)		8452.0			
TOTAL FUEL (10^6 BTU/YEAR)		9995.52			
ANNUAL EFFICIENCY (PERCENT)		84.6			

Table 9. Pipe With Twisted Tape (Metering Controller) Half Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	99.41	131.8	830.1	1100.9
25	20.33	81.56	108.96	1658.1	2215.2
35	46.65	63.64	86.76	2968.6	4047.2
45	43.39	45.63	63.86	1979.7	2770.8
55	26.69	27.49	40.68	733.8	1085.7
65	15.43	9.207	17.1	142.0	263.9
TOTAL LOAD (10^6 BTU/YEAR)		8312.3			
TOTAL FUEL (10^6 BTU/YEAR)		11483.7			
ANNUAL EFFICIENCY (PERCENT)		72.4			

Table 10. Pipe Without Turbulator (On/Off Controller) Half Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	99.25	123.73	828.7	1033.1
25	20.33	81.64	102.57	1659.8	2085.2
35	46.65	63.69	81.54	2971.4	3803.8
45	43.39	45.66	60.07	1981.1	2606.5
55	26.69	27.5	38.41	734.1	1025.3
65	15.43	9.212	16.35	142.1	252.3
TOTAL LOAD (10^6 BTU/YEAR)		8316.9			
TOTAL FUEL (10^6 BTU/YEAR)		10806.2			
ANNUAL EFFICIENCY (PERCENT)		77.0			

Table 11. Pipe with Wire Coil (On/Off Controller) Half Load at 10°F

BIN TEMP. °F	DAYS /BIN/YR	LOAD, 10^6 BTU /DAY	FUEL, 10^6 BTU /DAY	LOAD, 10^6 BTU /BIN/YR	FUEL, 10^6 BTU /BIN/YR
15	8.35	99.46	126.75	830.46	1058.4
25	20.33	81.6	104.76	1659.05	2129.9
35	46.65	63.66	83.42	2969.96	3891.4
45	43.39	45.63	61.45	1980.10	2666.5
55	26.69	27.5	39.28	734.01	1048.5
65	15.43	9.208	16.64	142.08	256.7
TOTAL LOAD (10^6 BTU/YEAR)		8315.7			
TOTAL FUEL (10^6 BTU/YEAR)		11051.4			
ANNUAL EFFICIENCY (PERCENT)		75.2			

Table 12. Pipe with Twisted Tape (On/Off Controller) Half Load at 10°F

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10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

A series of computer runs were made using DEPAB2 (the boiler simulation computer program). They include the runs for a fire-tube boiler "as is" (i.e., without turbulators), with wire-coil type turbulators, and with twisted-tape type turbulators, respectively. Output from these runs are used to evaluate the boiler seasonal performance values under the Washington, D.C. weather conditions. Results show that the turbulator increases the boiler seasonal efficiency from 2.87 to 6.08%.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

Boiler performance; boiler simulation; enhanced heat transfer; fire tube boilers; turbulators

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