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Applied Heat Transfer

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PennWell Books
PennWell Publishing Company
Tulsa, Oklahoma

E8361294

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To my mother, Rajammal Viswanathan

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PennWell Publishing Company
1421 South Sheridan Road/P.O. Box 1260
Tulsa, Oklahoma 74101

Library of Congress Cataloging in Publication Data
Ganapathy, V.
    Applied heat transfer.
    Includes bibliographical references.
    1. Heat—Transmission. I. Title.
TJ260.G28 621.402′2 81-17830
ISBN 0-87814-182-0 AACR2

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Printed in the United States of America

1 2 3 4 5 86 85 84 83 82

Applied Heat Transfer

Introduction

Several excellent textbooks have appeared so far on basic heat-transfer principles, but very few are on applications to real-life problems. Most of the books restrict their scope to heat-transfer calculations alone, neglecting the systems approach. Nor do they deal with thermal design of heat-transfer equipment. A design is complete only if all the following checks are done:

- Energy balance
- Preliminary sizing and surface area calculation
- Part load/off-design point calculations to see how the equipment performs at various operating points
- Metal-temperature calculations to check suitability of materials initially chosen and thickness or sizes
- Analysis for vibration and suggesting modifications before detailing
- Pressure-drop calculations for the streams involved in heat transfer and suggesting changes if pressure drops are critical
- Studying alternatives to bring down the total capitalized cost of the equipment

The next stage is detailed mechanical design. Unfortunately, engineering heat-transfer equipment has been dealt with in isolation in most books, with emphasis laid only on estimating heat-transfer coefficients. This is necessary but insufficient. Engineers should have a good idea of fluid-flow characteristics through the equipment. With steam generators, one must be able to estimate two-phase-flow pressure drop inside tubes of boiler furnaces and relate it to circulation, critical heat flux, and DNB. In the case of superheaters, flow in each element will not be the same, and nonuniformity will exist due to the mechanical

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arrangement of headers. Engineers must have an idea how to estimate this nonuniformity, since the tube with the lowest steam flow is the least cooled one and is likely to fail. Pressure drop of fluids inside and outside the tube banks of economizers, superheaters, finned-tube bundles, heat exchangers, and air heaters are critical. A 4-in. wc pressure drop in a waste-heat boiler for gas-turbine exhaust can reduce output by 1%. Hence fluid-flow behavior is pertinent to heat-transfer equipment design.

It is not sufficient if a design is done for a single design or operating point or tube geometry. In waste-heat boilers for gas-turbine exhaust, finned tubes are used and numerous variables are associated with them. Optimization must be performed to select the most economical combination of gas velocity, tube size, etc. Again, when designing a fire-tube boiler or condenser, tube-side velocity governs the overall heat-transfer coefficient. Optimum velocity may be obtained through life-cycle costing techniques. Examples are provided in the text to illustrate these points.

Performance calculations at off-design points are very important to know if problems in operation are likely. For example, in air heaters at lower loads, gas temperatures at the exit are likely to decrease. This may result in a lower metal temperature at the exit portion of the air heater and dew-point corrosion problems are likely. Engineers must think of ways and means to avoid this situation.

With the introduction of the concept of cogeneration and energy conservation, numerous plants are installing economizers to heat up feed water using waste gases. These may be plain or finned tube construction, and engineers should have an idea of the features of each and their economics. An example in the text compares the design with plain and finned tubes.

One of the problems encountered by engineers is estimating gas properties required for heat-transfer calculations. These are not readily available in most books. One appendix is devoted solely to estimating C_p, μ, and k for gaseous mixtures at atmospheric and elevated pressures. Graphs have also been presented that give C_p, μ, and k for common gases up to 400 atma.

The text is prepared to benefit a large cross section of readers. The book is divided into two parts: the main chapters and the appendices. Design of various heat transfer equipment is dealt with in the main chapters, while useful general information pertaining to basic heat transfer is appended.

The appendices can be used alone, because each is complete in itself. Various recent correlations from US and European literature (technical and trade) are cited, and examples are given to illustrate their use. Comparative studies of various correlations have also been made. Once the reader is familiar with the techniques involved in the appendices, he may apply them to the design of equipment discussed in the main chapters. Handy charts are also included in the appendices to save computational time.

Another aspect of the book is that simplified approaches to designing various kinds of equipment have been provided. These are extremely useful, especially if system limitations are existing. If a plant is interested in installing a waste-heat recovery boiler and space or gas-side pressure drop is limited, consulting engineers must design the unit to meet plant requirements. In such situations, a simplified approach to boiler design discussed in the text will come in handy. Equations have been developed to select the gas-side or tube-side velocity as well as geometry to limit pressure drops. Such an approach saves time and is sufficient for preliminary engineering proposals.

A chapter on fuels, combustion, and efficiency calculations is included. In engineering boiler surfaces or fired heaters, the starting point is estimating air and flue-gas quantities, partial pressures of triatomic gases, and losses occurring in these units and their efficiency. Also, properties of products of combustion of fossil fuels at various excess air levels have been computed.

In addition, information on selecting materials and sizing tubes per the ASME Code Practice is also provided, making the examples that are worked out as practical in character as possible.

A subject that is gaining importance in tube-bundle or heat-exchanger design is analysis for possible vibration and consequent damages to tubes or the exchanger. An appendix is included to illustrate the various mechanisms causing vibration, and examples have been worked out to check the adequacy of design from vibrational problems and noise. Although these checks are approximate, they are based on site-operational data.

This is not "yet another book" on heat transfer but is one that will be used often by a large cross section of engineers in their day to day work. Based on several years of engineering experience of the author, it may be used as a textbook in colleges and a reference book by consultants and professional engineers involved in engineering or operating heat-transfer equipment.

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1

Fuels and Combustion

This chapter deals with fuels, their typical analysis, combustion calculations, and various losses occurring in steam generators and fired heaters. A few examples are given to help show the conversion of fuel costs from \$/MM BTU to \$/lb or \$/cu ft. Typical examples that one comes across in industrial situations like estimating excess air from flue-gas analysis, determining partial pressures of water vapor and carbon dioxide if excess air is known, and quick estimates for combustion air and flue-gas quantities even if ultimate analysis is unknown are worked out. Handy charts, data sheets to simplify heat loss, and combustion calculations make this chapter extremely useful to engineers involved in thermal design or heat-balance calculations for steam generators and other fired process equipment.

Fossil fuels like coal, oil, and gas generate steam in boilers. In the case of fired heaters and waste-heat boilers, liquid or gaseous fuels are used widely. Engineers involved in heat-transfer equipment are interested in the process of combustion since its product is the source of energy for generating steam or heating process fluids.

Coal: Its Properties Related to Combustion

Coal is abundant in nature. It is grouped into three major types based on its properties: anthracite (geologically the oldest), bituminous, and lignite. Anthracite is mostly carbon with a little volatile matter. It is a slow-burning fuel, and not many applications of firing with it are found outside Great Britain. Bituminous coals, on the other hand, have more volatile matter and burn easily in a pulverized form. Their high volatile content makes them a good source for coke-oven gas production. Lignites have a large amount of volatile matter, including a high percentage of carbon dioxide (CO_2).

For engineers using coal for combustion and steam generation or for process heating, information on the following aspects is required:

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- proximate or ultimate analysis
- ash characteristics
- heating value
- grindability and free-swelling index

Proximate analysis determines moisture, volatile matter, fixed carbon, and ash. As it is approximate in nature, combustion or flue-gas heat-loss calculations using this analysis may be wrong. The ultimate analysis gives moisture, carbon, hydrogen, sulfur, oxygen, nitrogen, and ash in percentage by weight. Flue-gas analysis, combustion calculations, and heat-loss calculations are obtained more accurately when we have the ultimate analysis.

Typical coal analysis (as received) for a Pittsburg seam coal is given below:[1]

Proximate analysis, wt %		*Ultimate analysis, wt %*	
Moisture	2.5	Moisture	2.5
Volatile matter	37.6	Carbon	75.0
Fixed carbon	52.9	Hydrogen	5.0
Ash	7.0	Sulfur	2.3
	100.0	Nitrogen	1.5
		Oxygen	6.7
		Ash	7.0
			100.0

Ash characteristics of coal

Ash in coal creates problems in furnaces, heat-transfer surfaces, fans, and dust collectors. Most ash leads to higher dust content of flue gases, creating erosion problems. In boilers, typically 80% of the ash is carried away with flue gases. A low-melting ash deposits on heating surfaces, fouling them considerably. Ash deposits in furnaces can cause decreased furnace absorption and increased superheater steam temperatures. Also, all bituminous coals contain enough sulfur and alkali metals to produce corrosive ash deposits on superheaters and reheaters. The combination of gas and metal temperatures enhances corrosion effects.

Ash fusion temperatures are important to boiler designers. This is classified into four categories: initial deformation temperature, softening temperature, hemispherical temperature, and fluid temperature (Table 1–1).

TABLE 1–1
Ash Content and Ash Fusion Temperatures of Some U.S. Coals and Lignite

(Reprinted with Permission of Babcock and Wilcox)[1]

Rank	*Low Volatile Bituminous*	*High Volatile Bituminous*				*Subbituminous*	*Lignite*
	1	2	3	4	5	6	7
Seam	Pocahontas No. 3,	No. 9,	Pittsburg,	No. 6,	Utah	Wyoming	Texas
Location	West Virginia	OH 10	West Virginia	Illinois			
Ash, dry basis, %	12.3	14.10	10.87	17.36	6.6	6.6	12.8
Sulfur, dry basis, %	0.7	3.30	3.53	4.17	0.5	1.0	1.1
Analysis of ash, % wt							
SiO_2	60.0	47.27	37.64	47.52	48.0	24.0	41.8
Al_2O_3	30.0	22.96	20.11	17.87	11.5	20.0	13.6
TiO_2	1.6	1.0	0.81	0.78	0.6	0.7	1.5
Fe_2O_3	4.0	22.81	29.28	20.13	7.0	11.0	6.6
CaO	0.6	1.3	4.25	5.75	25.0	26.0	17.6
MgO	0.6	0.85	1.25	1.02	4.0	4.0	2.5
Na_2O	0.5	0.28	0.80	0.36	1.2	0.2	0.6
K_2O	1.5	1.97	1.60	1.77	0.2	0.5	0.1
Total	98.8	98.44	95.74	95.2	97.5	86.4	84.3

TABLE 1–1 *Cont'd*
Ash Content and Ash Fusion Temperatures of Some U.S. Coals and Lignite
(Reprinted with Permission of Babcock and Wilcox)[1]

Rank	*Low Volatile Bituminous*	*High Volatile Bituminous*				*Subbituminous*	*Lignite*
Initial deformation Temperature, °F							
Reducing	2,900+	2,030	2,030	2,000	2,060	1,990	1,975
Oxidizing	2,900+	2,420	2,265	2,300	2,120	2,190	2,070
Softening Temperature, °F							
Reducing		2,450	2,175	2,160		2,180	2,130
Oxidizing		2,605	2,385	2,430		2,220	2,190
Hemispherical Temperature, °F							
Reducing		2,480	2,225	2,180	2,140	2,250	2,150
Oxidizing		2,620	2,450	2,450	2,220	2,240	2,210
Fluid Temperature, °F							
Reducing		2,620	2,370	2,320	2,250	2,290	2,240
Oxidizing		2,670	2,540	2,610	2,460	2,300	2,290

TABLE 1–2

Analysis of Fuel Oils *(Reprinted with Permission of Babcock and Wilcox)*[1]

Grade of Fuel Oil, wt %	*No. 1*	*No. 2*	*No. 4*	*No. 5*	*No. 6*
Sulfur	0.01–0.5	0.05–1.0	0.2–2.0	0.5–3.0	0.7–3.5
Hydrogen	13.3–14.1	11.8–13.9	(10.6–13.0)*	(10.5–12.0)*	(9.5–12.0)*
Carbon	85.9–86.7	86.1–88.2	(86.5–89.2)*	(86.5–89.2)*	(86.5–90.2)*
Nitrogen	NIL–0.1	NIL–0.1	—	—	—
Oxygen	—	—	—	—	—
Ash	—	—	0–0.1	0–0.1	0.01–0.5
°API	40–44	28–40	15–30	14–22	7–22
lb/gal	6.87–6.71	7.39–6.87	8.04–7.30	8.1–7.68	8.51–7.68
Pour point, °F	0 to −50	0 to −40	−10 to 50	−10 to 80	15 to 85
Centistokes at 100 °F	1.4–2.2	1.9–3.0	10.5–65	65–200	260–750
HHV, BTU/lb	19,670–19,860	19,170–19,750	18,280–19,400	18,100–19,020	17,410–18,990

*Estimated

Viscosity of coal-ash slag provides information on its use in slag tap or cyclone furnaces. Units firing coals with severe ash-slagging tendencies require lower heat-release rates.

Heating value of coal

Gross or higher heating value (HHV) is the heat released by the combustion of unit quantity of the fuel. The net or lower heating value (LHV) is calculated as the heat produced by the fuel when all water in the product remains as vapor. When ultimate analysis of coal is known, Dulong's formula gives HHV:

$$\text{HHV} = 14{,}500\ \text{C} + 62{,}000\ (\text{H}_2 - \text{O}_2/8) + 4{,}000\ \text{S} \tag{1.1}$$

where C, H_2, O_2, and S are fractions by weight of carbon, hydrogen, oxygen, and sulfur on a fired basis. Dulong's formula is not accurate for subbituminous lignites, and errors of 4 to 6% are possible. If HHV is known, LHV is found as follows:

$$\text{LHV} = \text{HHV} - 9{,}720\ \text{H}_2 - 1{,}110\ \text{M} \tag{1.2}$$

Grindability indicates the easiness with which coals can be ground, and the free-swelling index is a measure of the behavior of coal when heated. ASTM D 409 and ASTM D 720 give the procedure for determining these.

Fuel-Oil Characteristics

Fuel oils are graded according to gravity and viscosity, the lightest being No. 1 and the heaviest No. 6. Nos. 5 and 6 require heating for satisfactory pumping and burning. Table 1–2 gives analysis of fuel oils. Viscosity of fuel oils is shown in Fig. 1–1.

Because of its low cost, No. 6 oil is used most widely for steam generation. Its ash content ranges from 0.01 to 0.5%; ash containing compounds of vanadium, sodium, and sulfur can be responsible for high- and low-temperature corrosion problems.

TABLE 1–3
HHV for Fuel Oil

°API	*HHV (BTU/lb)*
5	18,200
10	18,550
20	19,040
30	19,400
40	19,740

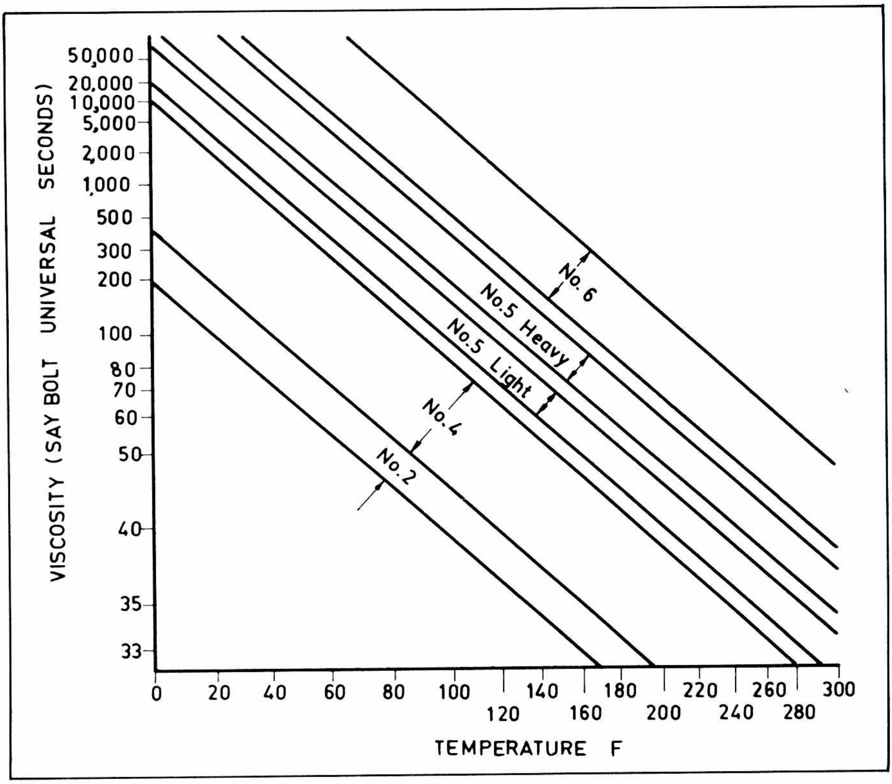

Fig. 1–1 *Viscosity of fuel oils (after* Steam, Its Generation and Use, *38th ed., © Babcock and Wilcox).*

Table 1–3 gives gross heating values for fuel oil based on API gravity.

$$°\mathrm{API} = \frac{141.5}{\text{sp gr at } 60/60\ °\mathrm{F}} - 131.5 \tag{1.3}$$

The heating value for an actual oil is obtained by correcting the heating value from Table 1–3 as follows:

$$\mathrm{HHV} = \mathrm{BTU/lb} \times \left[\frac{100 - (\mathrm{ash} + M' + S)}{100}\right] + 40.5\ S \tag{1.4}$$

where M′ and S are a percentage by weight of water and sulfur in the oil.

An approximate expression for the heating value of distillate and residual fuel oil is given below:

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