SERIES IN THERMAL & FLUID PHYSICS & ENGINEERING
SERIES EDITOR: G.F. HEWITT

# *Practical Thermal Design of Air-Cooled Heat Exchangers*

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# Dedication

*This book is dedicated to my parents, who would have been proud to see this work. And that is an understatement. To my dear wife, Kalpana, who has been supporting and inspiring me for over three decades now; to our daughter, Shilpi, our son (-in-law), Bappa, and their sons Sohum and Shivum; but most importantly, it is dedicated to the reader, whose approbation and appreciation would make all the toil worthwhile.*

# Acknowledgments

I am indebted to Almighty God for having given me the education, intelligence, opportunity, strength, and fervor to write this book.

I am also indebted to all those from whom I learned the design of air-cooled heat exchangers over the years, especially to Wim Bos and Peter van der Broek of Lummus Nederland B.V., who in 1971, initiated me on the path of air cooler design.

I will always be grateful to Cindy Mascone, ex-technical editor at Chemical Engineering Progress, and her one-time compatriot, Gail Nalven, who led me to believe that I could write a book. I will never forget Gail's words, "You do not know how prolific you are!" As for Cindy, she is the finest editor I have ever worked with.

This book might not have been possible without the wonderful exposition of air-cooled heat exchanger technology by Heat Transfer Research, Inc. (HTRI). My long experience in the field of air-cooled heat exchangers has been very largely honed on the platform of HTRI, whose software I have been using since 1974.

I am grateful to HTRI, Begell House, Hudson Products Corp., Moore Fans Ltd., TEMA (Tubular Heat Exchanger Manufacturers Association), and Cal Gavin Ltd. for permission to use some of their diagrams and photographs in this book. These have been duly acknowledged where they appear.

I am indebted to Bill Begell who decided to publish this book, and to all the people at Begell House who were responsible for its production. Special thanks go to Donna Thompson who did a splendid job of copyediting this book, as she did with the previous one on shell-and-tube heat exchangers. Donna, I have enjoyed working with you again.

How can I forget my good friend Graham Polley in the UK? It was he who led me to Bill in the first place.

I am thankful to Geoff Hewitt, who is the editor of the present series of books, for having readily accepted this book into his fold.

Thanks are also due to my wonderful friend Sam Chapple of Edmonton, Canada, who guided me on some important issues in the text.

I must also express my gratitude to another good friend, Lalit Shingal, who helped me with the reproduction of many diagrams that appear in the book.

What we are able to accomplish in our lives, whether professionally or otherwise, is the result of the Lord's grace and the encouragement and support we receive from myriad sources. This book is therefore truly a collaborative effort, and the credit belongs to the human fraternity at large, rather than to any individual.

# About the Author

Rajiv Mukherjee is a consultant in unfired heat transfer based in New Delhi, India. He has 36 years of experience in the thermal design, revamping, and troubleshooting of air-cooled and shell-and-tube heat exchangers, and considerable experience in the design of heat exchanger networks. He has written several articles in reputed journals and presented many papers at technical symposia. Rajiv has also served as faculty for numerous courses on heat exchanger design and operation, energy conservation, and heat exchanger networks, and presently teaches an intensive in-house refresher course on the design and operation of heat exchangers that can be offered at any plant site or office location around the world. He is an honors graduate in chemical engineering from Jadavpur University, Kolkata, India.

In his spare time, Rajiv enjoys reading (Swami Vivekananda and Kahlil Gibran are big favorites), writing, and listening to music. He lives in New Delhi with his wife, Kalpana. Their daughter, Shilpi, and her husband, Bappa, presently live with their sons, Sohum and Shivum, in Tokyo, Japan.

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**R. Mukherjee**

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# PREFACE

My desire to write this book was precipitated by the absence of such a "practical" book. Recent heat exchanger design literature has been predominantly occupied by proceedings of conferences. There is no book in the market that explains the logic of heat exchanger thermal design and gives practical suggestions and recommendations for actually designing industrial heat exchangers. So, having written my earlier book, *Practical Thermal Design of Shell-and-Tube Heat Exchangers*, which received a fairly good response, I decided to write a sequel—one on air-cooled heat exchangers.

The theoretical aspects of single-phase heat transfer and condensation have been very well presented in several books. So, what was really required was a practical "how-to-design" book with numerous worked-out examples or case studies to embellish or illustrate a particular technique, facet, or style of design. The thousands of air-cooled heat exchanger designs that I have been associated with over the last three decades have provided numerous examples. They say that one picture is more eloquent than a thousand words. If you extend this logic, one appropriate illustration by a case study is eminently more didactic than a long dissertation on a particular subject.

This book has been written in the same style, language, and format as the one on shell-and-tube heat exchangers. For the sake of convenience, both English and metric units have been used throughout the book. There are 26 case studies, all aimed at embellishing, illustrating, reinforcing, or demonstrating a feature, rationale, or methodology of design elaborated or advocated in the text. Not only are the case studies based on the HTRI software, the entire book is founded on the platform of HTRI know-how, which has become a way of life for me for almost three decades.

Being a "practical" book, theory is limited to a bare minimum, and the accent is on fundamentals, on design logic, on the interplay of parameters, on cause and effect, on understanding why things happen the way they do. For example, why does a light hydrocarbon condenser tend to have only four rows of tubes, whereas a heavy hydrocarbon liquid cooler tends to have more rows of tubes? Or why do we choose 1/2 in. (12.7 mm) high fins in certain situations but 5/8 in. (15.875 mm) high fins in others? Or why is the process fluid "break point" between an air-cooled heat exchanger and its downstream trim cooler related to the design ambient temperature? And many, many others.

This book has been written primarily for the heat exchanger thermal designer. However, I think it will also be useful to process engineers, a significant part of whose routine job is to specify heat exchangers. This book has not been written in an esoteric style for this very reason. Since operating aspects are also often discussed, I trust it will be of interest to plant operation specialists as well.

It is my fond hope that even B.S. and M.S. chemical and mechanical engineering students will find the book interesting, informative, and useful. I still remember when I was an undergraduate student—I used to long for more practical, real-life information about industrial practice. If one considers that many engineering graduates end up working in the chemical process industries, there may be a lot of merit in adding such a flavor to heat transfer in the university curriculum, as indeed it is to all other fields of human learning. The juxtaposition of industrial equipment design practice with basic theory will go a long way in making the subject more interesting and meaningful.

The thermal design of air-cooled heat exchangers is a fascinating activity—sometimes even more so than that of shell-and-tube heat exchangers—for the simple reason that there are more variables: even the coolant (air) flow rate is a variable! This book will have served its purpose if it can inspire the reader to consider the thermal design of air-cooled heat exchangers as a joyous activity rather than a mundane chore.

I will be grateful for any feedback regarding any aspect of this book, and the same may be sent to rajiv.mukherjee@vsnl.com or rajivmuk2003@yahoo.com.

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# CHAPTER 1

# *Introduction*

Although air is much more freely available than water and costs nothing, process cooling has historically been accomplished by cooling water. This is attributable to the much lower cost of cooling by water, thanks to its substantially higher thermal conductivity and lower temperature. However, with increasing shortages of cooling water and a consequent increase in its cost, air cooling has become more and more popular. Today, air-cooled heat exchangers (ACHEs) are a common sight in the chemical process industries (CPIs).

The first cost of an ACHE is much greater than that of a water-cooled heat exchanger for the same heat duty, but its operating cost is usually much less. The operating cost with water cooling comprises the cost of the initial raw water itself, makeup water, treatment chemicals, apportioned cost of the cooling tower, and of course the pumping cost. For air-cooled heat exchangers, the operating cost is only the cost of the power required to make the air flow across the tube bundles. Thus, on an overall cost basis, ACHEs often compare quite favorably with water-cooled heat exchangers.

The design of ACHEs comprises two distinct activities, namely, thermal design and mechanical design. In thermal design the basic sizing of the heat exchanger is accomplished, whereas in mechanical design the thicknesses and precise dimensions of the various components are determined and a bill of materials is produced. Detailed engineering drawings are then prepared based on which actual fabrication drawings are made. In this book, as the title suggests, we shall talk principally about thermal design.

With the availability of sophisticated software, there has been an undue dependence on them as “black boxes,” without the designer being truly in control of the design process and understanding the nuances of design. A proper and sound understanding of the fundamental principles and interplay of parameters is essential in order to produce an optimum design. The principal purpose of writing this book is to help the heat exchanger thermal designer attain such an understanding.

Presently, there is no book available on “practical” ACHE thermal design. This book is based on the author’s experience of over 36 years in the thermal design of ACHEs for the chemical process industry, and reflects many real-life situations that were far from straightforward. This book has been written in a structured, logical, and didactic manner, and special effort has been made at bringing out the interplay of parameters for a thorough understanding of basic issues.

As “*Example is better than precept*,” several case studies are presented in this book in order to vividly bring out a particular methodology, principle, or practice that has been advocated. The reader is invited to run these examples with further variations in the parameters being examined, in order to develop a comprehensive understanding.

It is well known that the thermal design of ACHEs is still largely an enigma, with far fewer engineering and fabricating companies practicing the trade than the thermal design shell-and-tube heat exchangers. This is really quite surprising, considering that thermal design of ACHEs is simpler and more straightforward than that of shell-and-tube heat exchangers! This book will have served its purpose if it encourages more companies to overcome this diffidence and take up the thermal design of ACHEs.

Now, coming to the individual chapters themselves, Chapter 2 dwells on the advantages and disadvantages of air cooling, while Chapter 3 discusses the optimization of air and water cooling. In some instances, only cooling by air need be employed, whereas in others only cooling by water is adequate. However, in the vast majority of cases that fall between these two extremes, cooling by both air and water is favorable.

Chapter 4 gives a detailed rundown of the various components and constructional features of ACHEs, since a good understanding of the same is vital to the thermal design of this equipment. This chapter will also be of considerable interest to mechanical designers of ACHEs, since it explains the implications of several constructional features on thermal design.

Chapter 5 discusses various basic concepts that form much of the foundation of knowledge for ACHE design. The simultaneous optimization of airside and tubeside calculations is certainly not an easy task. However, with the help of logical explanations, arguments, and case studies, the design methodology is made easy to understand and apply.

Chapter 6 is on the thermal design of condensing ACHEs. After a brief classification of condensers and a brief account of the mechanisms of condensation, practical guidelines for thermal design are discussed. These include isothermal, narrow-range and wide-range condensation, the effect of pressure, the handling of desuperheating and subcooling, nozzle sizing, and the handling of condensing profiles and physical property profiles.

In Chapter 7, with the help of numerous case studies, optimization of ACHEs is demonstrated vis-à-vis tube OD, fin height, fin spacing, number of tube rows, fan power consumption, tube pitch, and the number of tube passes.

In Chapter 8, physical properties and heat release profiles are discusses at length. The reader is offered guidance on how to feed heat release profiles, a matter that is not as simple as it may appear.

Chapter 9 explains why overdesign is provided, and elaborates on the modalities of overdesign for single-phase and condensing services.

After reviewing the various categories of fouling and the parameters that affect it, suggestions are offered in Chapter 10 on how to specify fouling resistance. Comprehensive guidelines are then suggested and analyzed in order to minimize fouling.

Chapter 11 is on the control of ACHEs, where various methods of control are discussed in detail. Unlike water-cooled shell-and-tube heat exchangers, ACHEs offer very good control on the process.

Chapter 12 deals with operating problems in air-cooled heat exchangers. Various potential problems and ways to avoid them are discussed for both the tubeside and the airside cases.

In Chapter 13, many special applications are elaborated on, including combined services, recirculation ACHEs, humidified ACHEs, tube inserts, variable finning density, natural convection, and vacuum steam condensers.

## CHAPTER 2

# *Advantages and Disadvantages of Air Cooling*

Let us take a look at the advantages and disadvantages of air cooling as compared to water cooling

## 2.1 Advantages of Air Cooling

Air cooling offers many advantages over water cooling. We have already discussed the cost advantage of air cooling over water cooling. Besides this advantage, the use of air as a cooling medium eliminates certain inherent disadvantages associated with water cooling:

*a*) The location of the cooler and thereby a plant is independent of a source of water supply such as a river or a lake, or even a sea; hence, the plant can be located in any geographic area. To use water as a cooling medium, however, the plant has to be located at a site close to a large natural body of water such as a lake, river, or sea. This could very easily entail a penalty in terms of transportation of raw materials or finished products.

*b*) Air coolers are far more environment friendly since thermal and chemical pollution of the source of water are eliminated. In once-through cooling water, such as with sea water, warmer water is returned to the body from which the water is drawn, thereby leading to a rise in temperature of that body of water. This has a direct adverse effect on the life and longevity of the aquatic plant and animal species inhabiting the body of water. In recirculating cooling water systems (which are the norm), the outlet warm water is cooled by a cooling tower so as to eliminate this increase in temperature of the discharge water with its associated adverse effect on aquatic life.

*c*) Maintenance costs are lowered considerably since frequent cleaning of the water side of coolers (necessitated by fouling such as scaling, biofouling, sedimentation, etc.) is eliminated.

*d*) The installation is simpler since water piping and water pumps are eliminated.

Another advantage with air coolers is that they continue to operate (although at a reduced capacity) by natural convection even when there is a power failure. In some cases, this can be as much as 60–70% of the design duty. In the case of water cooling, however, a power outage usually means a plant shutdown, which results in direct loss in production.

Yet another advantage with air cooling is that air-cooled heat exchangers offer very effective control of the process fluid outlet temperature (and thereby the heat duty) through the following various means:

a) switching fans on/off
b) use of two-speed motors
c) use of autovariable fans
d) use of louvers
e) use of variable-speed drives

These will be discussed in detail in Chapter 11.

On the other hand, water cooling does not render an effective means of control of the process fluid outlet temperature (and thereby the heat duty). This is because of two reasons: (a) the MTD is predominantly controlled by the cold end temperature difference which does not change with a reduction in the cooling water flow rate and (b) the cooling water film resistance is a very small percentage of the overall resistance to heat transfer. Consequently, a reduction in the cooling water flow rate has a negligible effect on the performance of a water-cooled cooler.

In an air-cooled heat exchanger, however, a reduction in the air flow rate has a much more pronounced effect on the performance of the cooler because both the MTD and the overall heat transfer coefficient change significantly. This is because the airside heat transfer coefficient controls the overall heat transfer resistance quite strongly, and the MTD also varies significantly with a change in the air flow rate, and thereby the outlet air temperature. This is illustrated in the following case study.

## CASE STUDY 2.1: EFFECT OF REDUCTION OF AIR FLOW RATE

A quantity of 1,700,000 lb/h (771,115 kg/h) of hot water is to be cooled from 174°F (78.9°C) to 140°F (60°C), representing a heat duty of 57.665 M Btu/h (14.53 M kcal/h). The allowable pressure drop of hot water is 10 psi (0.7 kg/cm$^2$) and its fouling resistance is 0.001 h ft$^2$°F/Btu. For cooling by air, the design air temperature is 107°F (41.7°C). For cooling by water, the cooling water inlet temperature is 93°F (33.9°C), its allowable pressure drop is 10 psi (0.7 kg/cm$^2$), and its fouling resistance is 0.002 h ft$^2$°F/Btu (0.0004 h m$^2$°C/kcal).

The air-cooled heat exchanger design was prepared first and its principal construction parameters are indicated in Table 2.1a. The total air flow rate was 7,700,000 lb/h (3,493,700 kg/h). To demonstrate the effect of a reduction in the total air flow rate, the same was changed to 6,900,000 lb/h (3,130,000 kg/h) and then to 6,100,000 lb/h (2,767,000 kg/h). The principal performance parameters for all three total air flow rates are shown in Table 2.1b. It will be seen that there is a significant reduction in the overdesign with a lowering in the air flow rate, from 6.2% in the first case to –2.9% in the second case, and finally to –13.7% in the third case. This is due to an appreciable reduction in both the MTD [from 33.2°F (18.4°C) to 28.6°F (15.9°C)] and the airside heat transfer coefficient [from 178.8 Btu/h ft$^2$°F (873 kcal/h m$^2$°C) to 163.2 Btu/h ft$^2$°F (797 kcal/h m$^2$°C)].

Next, the water-cooled hot water cooler design was then prepared, the principal construction parameters of which are shown in Table 2.1c. The cooling water flow rate is 3,400,000 lb/h (1,542,200 kg/h). In order to demonstrate the effect of a reduction in the coolant flow rate, the same was reduced by the same amount as the air flow rate in the case of the air-cooled heat exchanger design. The principal performance parameters of all three designs are shown in Table 2.1d. It will be seen that the reduction in overdesign is far less than that of the air-cooled heat exchanger, from 7.3% in the first case to 3.5% in the second

**Table 2.1a:** Principal construction parameters of air-cooled hot water cooler

| | |
|---|---|
| No. of bays in parallel | 4 |
| No. of bundles per bay | 2 |
| No. of tubes per row | 46 |
| No. of tube rows × no. of tube passes | 5 × 2 |
| Tube/fin material | CS/Aluminum |
| Tube OD × thickness | 1 in (25.4 mm) × 12 BWG (2.77 mm) |
| Tube length, ft (m) | 34 (10.36) |
| Fin height × fin thickness | 5/8 in (15.875 mm) × 0.016 in (0.4 mm) |
| Fin density | 11 per in (433 per meter) |
| Transverse pitch, in (mm) | 2.625 (67) |
| Bundle width, ft (m) | 10.2 (3.11) |
| Total bare tube area, ft$^2$ (m$^2$) | 16,047 (1491) |
| Total extended area, ft$^2$ (m$^2$) | 381,080 (35,416) |
| No. of fans per section × fan dia., ft (m) | 2 × 14 (4.27) |
| Motor power, HP (kW) | 30 (22.4) |

**Table 2.1b:** Effect of variation in air flow rate on performance of air-cooled hot water cooler

| Total air flow rate, lb/h (kg/h) | | 7,700,000<br>(3,492,700) | 6,900,000<br>(3,130,000) | 6,100,000<br>(2,767,000) |
|---|---|---|---|---|
| Air outlet temperature, °F (°C) | | 138.1 (58.9) | 141.7 (60.9) | 146.3 (63.5) |
| Static pressure, in. WC (mm WC) | | 0.43 (10.9) | 0.35 (8.9) | 0.3 (7.6) |
| Tubeside pressure drop, psi (kg/cm$^2$) | | 2.1 (0.15) | 2.1 (0.15) | 2.1 (0.15) |
| Heat transfer coefficient, Btu/h ft$^2$°F (kcal/h m$^2$°C) | Tubeside | 838 (4092) | 838 (4092) | 838 (4092) |
| | Airside (bare tube) | 178.8 (873) | 171.1 (835) | 163.2 (797) |
| | Overall | 114.9 (561) | 111.7 (545) | 108.3 (529) |
| MTD, °F (°C) | | 33.2 (18.4) | 31.2 (17.3) | 28.6 (15.9) |
| Overdesign, % | | 6.2 | –2.9 | –13.7 |
| Absorbed power, HP (kW) | | 26.5 (19.7) | 19.7 (14.7) | 14.2 (10.6) |

**Table 2.1c:** Principal construction parameters of water-cooled hot water cooler

| | |
|---|---|
| TEMA Type | AEL (Fixed tubesheet) |
| No. of shells | 1 |
| Shell ID, in. (mm) | 45 (1143) |
| No. of tubes × no. of tube passes | 1578 × 1 |
| Tube OD × thickness, in. (mm) | 0.75 (19.05) × 14 BWG (2.108 mm) |
| Tube length, ft (m) | 20 (6.1) |
| Tube pitch, in. (mm) | 1.0 (25.4) triangular |
| Type of baffles × baffle cut orientation | Double segmental × horizontal |
| Baffle spacing, in (mm) × no. of tube rows overlap | 19 (483) × 6 |
| Connections: shellside/tubeside, nominal, in (mm) | 16 (400)/20 (500) |
| Heat transfer area, ft$^2$ (m$^2$) | 6083 (565) |

case, and finally to 0.1% in the third case. This is because although there is a similar reduction in the overall heat transfer coefficient as in the case of the air-cooled heat exchanger, the drop in the MTD is far less.

## 2.2 Disadvantages of Air Cooling

Let us now consider the limitations of air-cooled heat exchangers as compared to water-cooled heat exchangers. This is a comprehensive list and only some of them will be presented for a particular situation or application.

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