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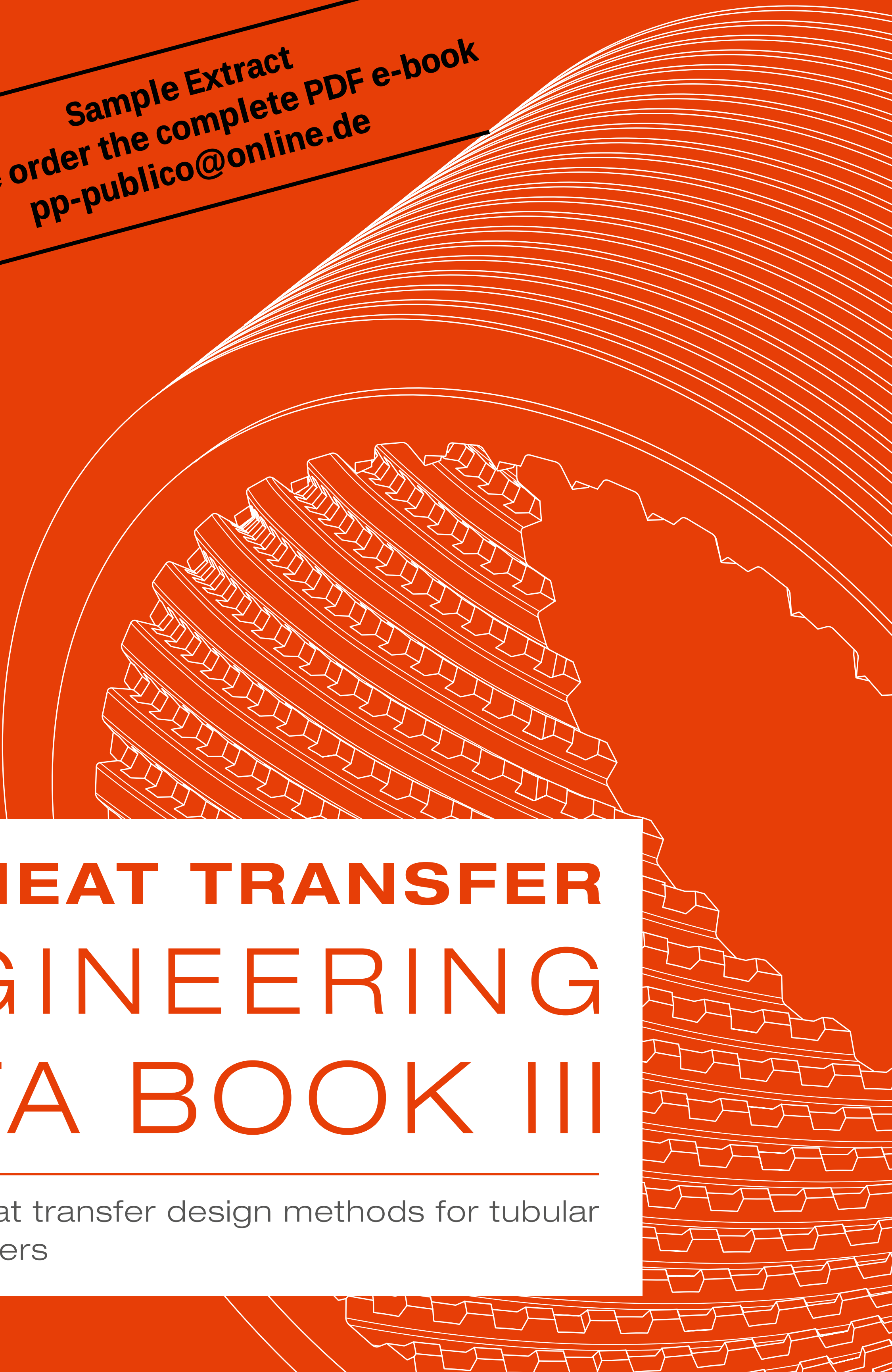

THE HEAT TRANSFER ENGINEERING DATA BOOK III

Enhanced heat transfer design methods for tubular heat exchangers

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PREFACE OF THE EDITOR

The Heat Transfer Engineering Databook III has become a benchmark and valuable reference in all work and research in heat transfer engineering. The manual provides information and discussions on basic principles of heat transfer and heat transfer design methods.

We wish to express our appreciation to Prof. John R. Thome for authorship of this important manual as well as to Wolverine Tube Inc. for enabling this.

Wieland-Werke AG now presents this new edition of *The Heat Transfer Engineering Databook III* in a revised and modern online format. We're glad to provide the heat transfer community with this benchmark for heat transfer knowledge.

Bernd Graßhof, Wieland-Werke AG
Ulm, October 2016

PREFACE OF THE AUTHOR

Welcome to the new edition of *The Heat Transfer Engineering Data Book III*. This book has been written primarily with heat transfer engineers in mind but also for research engineers who want to get caught up on the latest advances in heat transfer design methods for tubular heat exchangers. The objectives of the book are to present a limited review of the basic principles of heat transfer and then describe what I currently consider to be the best thermal design methods available. Hence, each chapter presents a detailed state-of-the-art review of heat transfer and fluid flow research of practical interest to heat exchanger designers, manufacturers and end users; however, for more exhaustive treatments the reader is recommended to go to the many references and other reviews cited.

The idea to make this a web-based book is to make this information more readily available to the reader. New chapters will be added as they become ready and also the existing chapters will be updated with new methods as they appear in the literature every few years to keep this whole reference book up to date. Also, Chapter 1 presents a video gallery of heat transfer and flow phenomena that I think will be quite useful to heat transfer engineers who have never had the chance to see what is in fact happening inside their heat exchangers!

I, myself, have pulled *The Heat Transfer Data Book II* down from the shelf many times over the years to look for design information to use my own engineering work. Data Book II contains much valuable information that has not been repeated in *Data Book III*.

Finally, I would like to thank Wolverine Tube Inc. for inviting me to write this new edition of *The Heat Transfer Engineering Data Book III*, in particular Massoud Neshan and Petur Thors of the Research and Development group.

John R. Thome, Author
Lausanne, June 2006

ABOUT THE AUTHOR

John R. Thome is Professor of Heat and Mass Transfer at the Ecole Polytechnique Fédérale de Lausanne (EPFL), Switzerland since 1998. He is the author of five books and has published widely (over 220 journal papers in the past 18 years) on the fundamental aspects of microscale and macroscale two-phase flow, boiling/condensation heat transfer and micro-two-phase cooling systems. He has proposed over 100 two-phase flow and heat transfer prediction methods applicable to macro and micro scale processes, including his widely used flow pattern based methods. He received the ASME Heat Transfer Division's Best Paper Award in 1998 for his work published in the *Journal of Heat Transfer,* the Very Highly Commended Paper Award from the *International Journal of Refrigeration* for 2011-2012, the UK Institute of Refrigeration's J.E. Hall Gold Medal in 2008 for his work on microscale refrigeration heat transfer, the 2010 ASME Heat Transfer Memorial Award for his career work on flow pattern based heat transfer models for macro and micro-scale flows, and an ASME 75th Anniversary Medal from the Heat Transfer Division. He received the ICEPT-HDP 2012 Best Paper Award on his paper on a 3D-IC prototype with interlayer cooling built with over 13'000 TVS's inside and the ASME *Journal of Electronics Packaging* Best Paper Award at IMECE in November 2014. He most recently has been awarded the 2016 Nusselt-Reynolds Prize. He founded the *Virtual International Research Institute of Two-Phase Flow and Heat Transfer* in 2014, now with 19 participating universities to promote research collaboration and education (see http://2phaseflow.org).

TABLE OF CONTENTS

CHAPTER 1 – VIDEO GALLERY OF FLOW PHENOMENA

Provides a video gallery of flow and heat transfer phenomena and their descriptions, along with links to other chapters that pertained to it.

CHAPTER 2 – DESIGN CONSIDERATIONS FOR ENHANCED HEAT EXCHANGERS

Covers the thermal design considerations, mechanical design considerations, cost considerations, parametric studies on thermal designs, case studies of actual interventions and other practical information.

CHAPTER 3 – SINGLE-PHASE SHELL-SIDE FLOWS AND HEAT TRANSFER

Chapter 3 presents the most recent open literature version of the stream analysis method for shell-side flows in addition to the older graphical presentation of the Delaware method in The Heat Transfer Engineering Data Book II.

CHAPTER 4 – ENHANCED SINGLE-PHASE LAMINAR TUBE-SIDE FLOWS AND HEAT TRANSFER

Provides a treatment of correlations for predicting heat transfer and pressure drop for intube flows in corrugated tubes, ribbed tubes, finned tubes and with twisted tape inserts. It covers laminar flow and laminar flow augmentation.

CHAPTER 5 – ENHANCED SINGLE-PHASE TURBULENT TUBE-SIDE FLOWS AND HEAT TRANSFER

Provides a treatment of correlations for predicting heat transfer and pressure drop for intube flows in corrugated tubes, ribbed tubes, finned tubes and with twisted tape inserts. It covers turbulent flow and turbulent flow augmentation.

CHAPTER 6 – HEAT TRANSFER TO AIR-COOLED HEAT EXCHANGERS

Provides design methods for heat transfer and pressure drop to plain, wavy, corrugated, etc. plate-fin geometries typical of air-conditioning coils.

CHAPTER 7 – CONDENSATION ON EXTERNAL SURFACES

Provides detail on condensation outside low finned tubes and enhanced condensing tubes, condensation of mixtures, tube row effects and intertube flow patterns, etc. It also includes more fundamentals that designers are interested in on effects of vapor shear, interfacial waves, condensate retention, etc.

CHAPTER 8 – CONDENSATION INSIDE TUBES

Provides design methods for condensation inside plain and microfin tubes.

CHAPTER 9 – BOILING HEAT TRANSFER ON EXTERNAL SURFACES

Provides design methods for boiling outside plain, low-finned and enhanced tubes, evaporation of mixtures, etc. as single tubes and tube bundles. It includes the most widely used plain tube correlations and presents methods available for enhanced tubes and describes the fundamentals of pool boiling (nucleation, bubble dynamics, peak heat flux, etc.).

CHAPTER 10 – BOILING HEAT TRANSFER INSIDE PLAIN TUBES

Provides details on vertical and horizontal plain tube design methods.

CHAPTER 11 – BOILING HEAT TRANSFER INSIDE ENHANCED TUBES

Provides details on microfin tubes, twisted tape inserts, corrugated tubes and porous coatings. It also presents the concepts of vertical and horizontal boiling and design methods.

CHAPTER 12 – TWO-PHASE FLOW PATTERNS

Provides flow pattern maps for vertical and horizontal intube flows (including Thome's flow pattern map which is becoming increasingly popular for adiabatic and evaporating flows). It also presents a shell-side flow pattern map and some background theory on transition from one regime to another.

CHAPTER 13 – TWO-PHASE PRESSURE DROPS

Provides a complete treatment of prediction of two-phase pressure drops for intube flows and shell-side flows. It also addresses oil effects on two-phase pressure drops.

CHAPTER 14 – FALLING FILM EVAPORATION

Presents a summary of the status of falling film evaporation on the outside of horizontal tubes and tube bundles for plain and enhanced tubes.

CHAPTER 15 – THERMODYNAMICS OF REFRIGERANT MIXTURES AND REFRIGERANT-OIL MIXTURES

Presents an introduction to phase equilibria of mixtures that is useful to mechanical engineers. It shows the use and preparation of enthalpy curves for designing evaporators and condensers with mixtures. It also covers Thome's Thermodynamic Approach for modeling refrigerant-oil mixtures to show oil effects on the bubble point and enthalpy change of evaporating refrigerants that are important to include in the calculation of LMTD and energy balances.

CHAPTER 16 – EFFECTS OF OIL ON THERMAL PERFORMANCE OF HEAT EXCHANGERS

Covers the effects on heat transfer and pressure drops of oil on intube evaporation in plain and microfin tubes. It also covers the effects of oil on pool boiling and bundle boiling on plain and enhanced tubes.

CHAPTER 17 – VOID FRACTIONS IN TWO-PHASE FLOWS

Presents the basic theory and predictions methods for the two-phase flows in vertical and horizontal channels and over tube bundles.

CHAPTER 18 – POST DRYOUT HEAT TRANSFER

Covers the heat transfer process and prediction method for describing heat transfer in the post dryout regime.

CHAPTER 19 – FLOW BOILING AND TWO-PHASE FLOW OF CO_2

Addresses experimental studies and prediction methods for CO_2, together with some comparisons of these methods to experimental databases.

CHAPTER 20 – TWO-PHASE FLOW AND FLOW BOILING IN MICROCHANNELS

Addresses both experimental studies and predication methods for microchannels, together with some comparisons of these methods to experimental databases and to one another.

CHAPTER 21 – CONDENSATION IN MICROCHANNELS

Addresses experimental studies and predication methods for condensation inside small channels, together with some comparisons of these methods to experimental data and to one another.

Provides a list of all nomenclatures and their definitions.

Provide a list of resources that were used to write The Heat Transfer Engineering Data Book III.

WELCOME TO THE ENGINEERING DATA BOOK III CALCULATOR

V1.06.2006, (June 2006 Version)

INTRODUCTION

This Calculator is based on thermal design methods described in The Heat Transfer Engineering Data Book III.

It was primarily designed for **educational purposes**. Because it reflects many methods presented in the Data Book III, it can also be used by heat transfer engineers or research engineers to try out and compare different methods, generate two-phase flow pattern maps, etc.

The use of this file will allow you to quickly understand the application of many methods available in Data Book III.

IMPORTANT RECOMMENDATIONS

We strongly recommend you to download Data Book III and to read it before using this Calculator. This Calculator is a complement to the Data Book III. Reading the Data Book III will allow you to correctly choose the method of calculation you need in relation to the problems you are solving.

Because Data Book III includes recently published research work, it is updated constantly. If you want to be up to date with the current evolutions in single and two-phase flows, heat transfer and pressure drops, we recommend you to regularly check for new updates of the Data Book III and this Calculator.

In this Calculator, the various methods are referred to by the name of the author of the method. Refer to the appropriate chapter in Data Book III to see details of the method.

HOW TO USE

The use of this Calculator is very easy and should not present any difficulties. First, "Enter the Menu". In the Menu, choose the calculation that you with to perform. In the green boxes, enter the values that correspond to your problem and the results will be displayed automatically. Thanks to the "spin buttons" (that is the up and down buttons to click on), you can interact with the graphic output and see how the output values are modified.

Note that anywhere there is a "**spin button**", negative values and values smaller than 1.0 must be entered manually (for instance, for saturation 'temperatures below 0 °C)

Results can be printed out or tabular data exported by the user. **NO TECHNICAL ASSISTANCE IS PROVIDED**.

FLUID PROPERTIES

The Calculator has automatic fluid properties for a few selected fluids. These can be accessed by the “drop down menu” of fluids and their saturation temperature by the “spin buttons” within the range of the lookup file. The user can also specify his/her own fluid properties by choosing “Your-Own”. The properties for “Your-Own” fluid are filled in manually for the saturation temperatures of your interest and they are accessed from the main “Menu” by clicking “Enter Your-Own Fluid Properties”.

The Authors
Prof. John R. Thome
Ricardo J. Da Silva Lima

DISCLAIMER

Although much work has been invested in preparing of this Calculator, minor errors may exist. Therefore, like a book, only the final user is responsible for any damage or loss caused by the results provided by this Calculator. Neither the authors nor Wieland-Werke AG can be held responsible for any damage or loss caused by the results provided by this Calculator.

This Calculator is provided free for use and cannot be sold or modified by the user. Any contents used by the user from this Calculator must quote The Heat Transfer Engineering Data Book III as a reference source.

By clicking the button “**AGREE and download**” below, you hereby **read** and **agree** to this disclaimer. The calculator application will be downloaded once you click on the “**AGREE and download**” button below.

AGREE
and download

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CHAPTER 1 – VIDEO GALLERY OF FLOW PHENOMENA

Summary: Numerous videos have been assembled here for two-phase flows and heat transfer phenomena (and still more will be added in the future) and are available here for the reader to view. Presently, only two-phase videos are shown but videos of single-phase enhancement phenomena will be included in the future.

1.1 INTRODUCTION TO THE VIDEO GALLERY

The motive behind the preparation of this video gallery is to make videos of single-phase and two-phase flow and heat transfer phenomena available for general viewing. For thermal designers normally performing computer calculations on heat exchangers, this is an opportunity for them to actually see what some of the processes really look like, albeit in idealized test conditions. The idea is also to make this chapter a forum to display interesting videos of such phenomena for others to see.

Note: Since the original video files are typically too large (5–40 Megabits) to view directly via the internet, the videos shown have had to cut to short time sequences (typically 2 seconds or less) that are looped to give the sensation of a continuous process and also processing of the images has been applied to achieve smaller file sizes, but at a small lose of quality. Some patience may be required on behalf of the reader to view these video files via the Internet.

To use this chapter: The chapter is organized by type of flow. Within each section, videos are listed by the flow process they show; the reader needs only to click on the video of his choice on the list to see the video and also obtain a brief description of the test setup and experimental conditions.

1.2 TWO-PHASE FLOW PATTERNS IN HORIZONTAL TUBES

Figure 1.1 depicts a two-phase flow pattern map for flow in a horizontal tube, illustrating the types of two-phase flow patterns typical of these flows and the range of conditions where particular flow regimes occur. Within a horizontal evaporator tube, Figure 1.2 depicts a composite diagram of the flow patterns that may be encountered when going from a subcooled liquid to complete evaporation. Similarly, Figure 1.3 shows composite diagrams of flow patterns confronted in condensation at high and low flow rates. The videos in this section, listed below, show numerous examples of these flows.

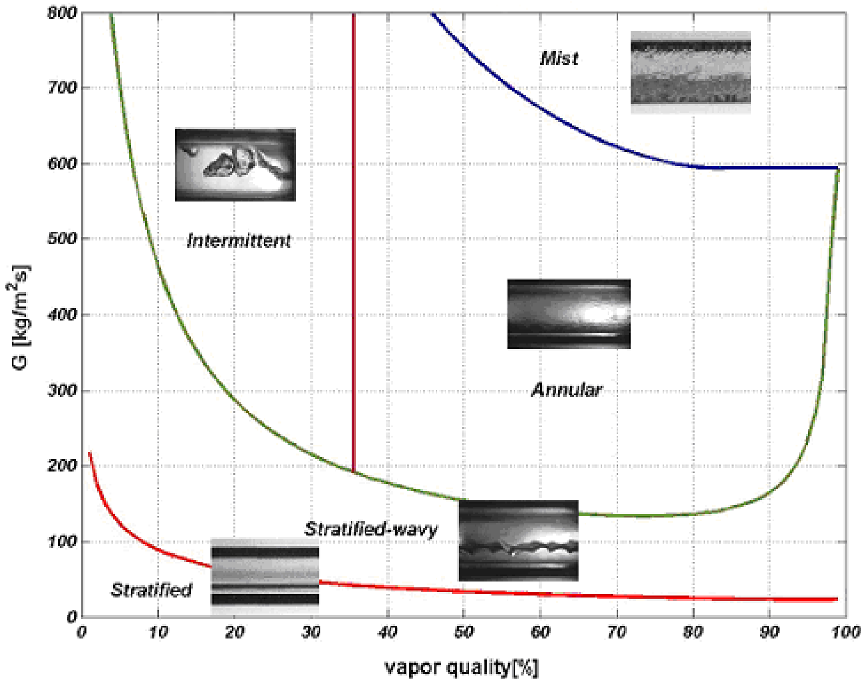

Fig. 1.1 Flow pattern map for R-22 at a saturation temperature of 5 °C (41 °F) showing transition boundaries between two-phase flow regimes [where G is the mass velocity of the liquid + vapor inside the cross-section of the tube of internal diameter d = 13.82 mm (0.544 in.)]

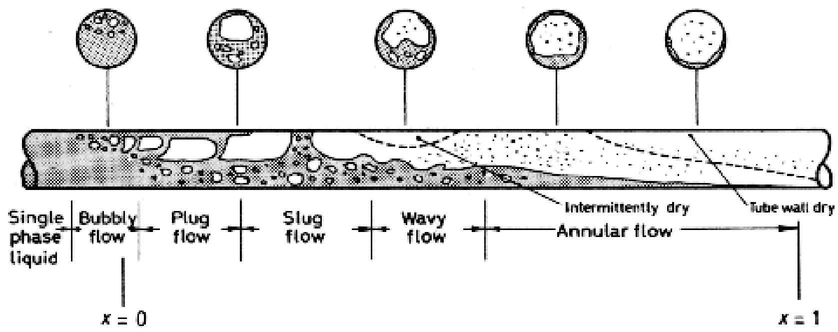

Fig. 1.2 Illustration of two-phase flow patterns occurring in horizontal evaporator tube

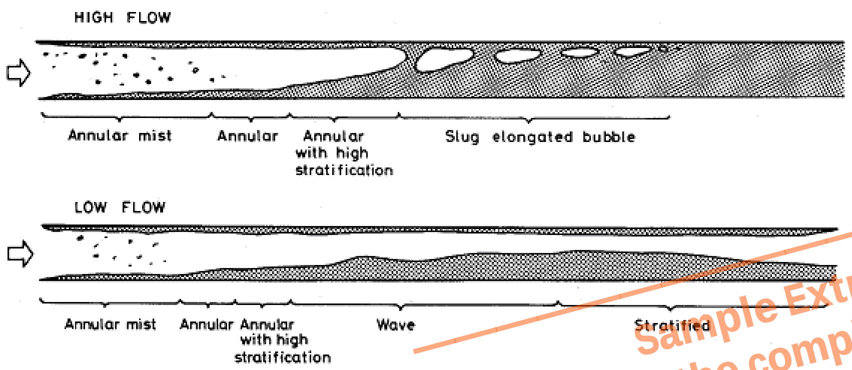

Fig. 1.3 Illustration of two-phase flow patterns occurring in horizontal condenser tubes

LIST OF VIDEOS

(click on the one you wish to see)

Video 1.2.1: Bubble flow.

The video displays flow of isolated bubbles inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. This flow is at a moderate mass velocity at a very low vapor quality and the bubble is essentially the initial step towards arriving at a plug flow. The fluid is ammonia at 5 °C (41 °F). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, Favrat and Thome (2002).

Video 1.2.2: Stratified-wavy flow.

The video displays a stratified-wavy flow (liquid in bottom and vapor in top of tube) inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5 °C (41 °F), a vapor quality of 0.20 and mass velocity of 26 kg/m^2s (19126 $lb/hr\ ft^2$). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, Favrat and Thome (2002).

Video 1.2.3: Plug/slug to intermittent flow transition.

The video displays a plug/slug flow at relatively low vapor quality inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5 °C (41 °F), a vapor quality of 0.06 and mass velocity of 180 kg/m^2s (132408 $lb/hr\ ft^2$). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, Favrat and Thome (2002).

Video 1.2.4: Annular flow.

The video displays an annular flow (liquid in an annular film on tube perimeter and vapor in center of tube) at relatively high vapor quality inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5 °C (41 °F), a vapor quality of 0.80 and mass velocity of 122 kg/m^2s (89743 $lb/hr\ ft^2$). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, Favrat and Thome (2002).

Video 1.2.5: Annular flow with partial dryout.

The video displays an annular flow with partial dryout around the upper perimeter (liquid in bottom and vapor in top of tube) at relatively high vapor quality (essentially a stratified-wavy flow created by the partial dryout around upper perimeter of the tube) inside a horizontal sightglass of 14.0 mm (0.551 in.) internal diameter. The fluid is ammonia at 5 °C (41 °F), a vapor quality of 0.80 and mass velocity of 41 kg/m^2s (30160 $lb/hr\ ft^2$). The video was taken by Dr. O. Zürcher in collaboration with Profs. J.R. Thome and D. Favrat at the Swiss Federal Institute of Technology Lausanne (EPFL). For a description of the test facility, refer to: Zürcher, Favrat and Thome (2002).

Video 1.2.6: Condensation flow regimes in plain tube.

The video displays the exit of a horizontal condenser tube cut at a 45° degree angle and situated inside a viewing chamber. The view is from the side. First, a flow pattern map is shown illustrating two superficial vapor velocities, JG, that were studied, plotted versus the Martinelli parameter, Xtt. The inside diameter of the tube is 8.0 mm (0.315 in.). The fluid is R-134a at 40 °C (104 °F), vapor qualities (x) of 0.49 and 0.26, and mass velocities (G) of 200 and 400 kg/m^2s (147120 and 294240 $lb/hr\ ft^2$). The video was taken under the direction of Prof. Alberto Cavallini at the University of Padova, Padova, Italy. For a description of their test facility and related investigation, refer to: Censi et al. (2003). For a description of their flow pattern map, refer to: Cavallini et al. (2002).

CHAPTER 2 – DESIGN CONSIDERATIONS FOR ENHANCED HEAT EXCHANGERS

Summary: This chapter focuses on heat transfer augmentation of tubular heat exchangers and describes existing and prospective applications of tubular heat transfer augmentations to a wide range of industries. Thermal, mechanical and economical considerations of particular importance are also presented.

2.1 INTRODUCTION

Enhanced tubes are used extensively in the refrigeration, air-conditioning and commercial heat pump industries while, in contrast, their consideration for use in the chemical, petroleum and numerous other industries is still not standard practice, although increasing. Designing enhanced tubular heat exchangers results in a much more compact design than conventional plain tube units, obtaining not only thermal, mechanical and economical advantages for the heat exchanger, but also for the associated support structure, piping and/or skid package unit, and also notably reduced cost for shipping and installation of all these components (which often bring the installed cost to a factor of 2 to 3 times that of the exchanger itself in petrochemical applications). The compact enhanced designs also greatly reduce the quantities of the two fluids resident within the exchanger, sometimes an important safety consideration. This chapter describes some of the practical considerations and advantages regarding the use of enhanced tubes and tube inserts in tubular heat exchangers and provides some guidelines for identifying their applications.

2.2 THERMAL AND ECONOMIC ADVANTAGES OF HEAT TRANSFER AUGMENTATIONS

There are many thermal advantages of utilizing augmentations that must be weighed against their higher cost relative to plain tubing and their economic benefit on plant operation. For many small increases to production capacity (10 to 30 %), the purchase and installation of completely new exchangers cannot be justified economically. However, when the heat exchangers are the "bottleneck" of a unit operation, then augmentations may be the right solution.

The principal advantage of introducing an augmentation is the possibility of substantially increasing thermal duty to meet the needs of new process conditions or production goals. This can be achieved either by:

1. Installing removable inserts inside the tubes,
2. Replacing a removable tube bundle with a new enhanced tube bundle,
3. Replacing the heat exchanger with a new enhanced tube heat exchanger of the same size or smaller.

The first two of these interventions can be completed without any modifications to the heat exchanger itself while all three can be implemented without changes to the original piping connections and to its supports. Hence, these interventions have the benefit of a minimum effect on the operating schedule of the production plant.

What about replacements of existing installed units?

As a prime example of this latter point, a removable tube bundle is easily replaced during shutdown by a new enhanced tube bundle. Or, a fixed tubesheet unit can be partially replaced by using the same heads, piping and supports. Tube inserts, on the other hand, can be installed inside the tubes of an existing exchanger during a normally scheduled shutdown, resulting in no lost production. The installation may require that some (or all) of the pass partition plates in the heads be removed to reduce the number of tube passes and thus meet pressure drop limitations when installing twisted tapes, especially for laminar flows. These types of interventions have very high payback ratios and plant operating reliability because of their simplicity and avoid the necessity of purchasing a new larger plain tube unit, which would require costly engineering services and expensive changes to the heat exchanger supports, its foundation and piping and also loss of production during these modifications.

What about new units in new plants?

For new heat exchangers, a well-optimized plain tube unit is normally the easy way out for heat exchanger designers, even though they unwittingly are often paying a premium of 20–50 % in the cost of the unit compared to an enhanced unit for the same service. Another consideration regards difficult applications where space is not available for two or more exchangers in parallel or where weight/bundle removal restrictions on units mounted on structures is a problem, and these are situations where heat transfer augmentations have been used to advantage by well informed heat exchanger designers.

What about cost savings?

The cost savings for appropriate applications of enhanced tubes to shell-and-tube heat exchangers in the petrochemical industries typically range from $10,000 to $200,000 per unit or more. Hence, several of these interventions a year easily justifies the engineering cost for evaluating otherwise conventional designs for appropriate use of an enhanced tube, such as a Tube Trufin or Turbo-Chil tube with internal and external enhancements (internal helical ribs and external low fins).

What about alloy tubes?

When utilizing high alloy tubes in heat exchangers (stainless steel, titanium, nickel alloys, duplex stainless steels, etc.), applying the appropriate augmentation can very significantly reduce their first cost. The augmentation may not only reduce the cost of the tubing, but also those of the heads and tubesheets (smaller diameters, smaller wall thicknesses, fewer tube holes to drill, less alloy cladding material, etc.). Even for conventional carbon steel heat exchangers, if the entire cost of the heat exchanger is included as it should be its total cost to the plant, a more compact, lighter weight enhanced shell-and-tube unit can greatly reduce the cost of shipping and installation. It is often estimated that the installed cost is 2 to 3 times the cost of the heat exchanger itself and hence a smaller enhanced unit will achieve a significant first cost savings when the true total cost is considered.

What are typical prices per foot or meter of enhanced tubing?

These are difficult to describe in a simple set of tabular values since their prices are very dependent on the particular tube material involved (primarily related to its hardness and hence resistance to deformation during the enhancement production process) and the wall thickness specified and the base cost of the bare tube. In general, the enhanced tube cost multiplying factor falls as the base tube material cost increases. Price information is readily available by contacting the enhancement's manufacturer (Wieland Thermal Solutions) for an offer. A doubly-enhanced tube version is also often available for the application (enhanced on the tube-side as well as on the shell-side) and it typically is the best thermal and economic choice.

What about heat exchanger cost savings?

As a quick measure, a thermal designer is tempted to compare an enhanced tube on a cost per foot basis versus its equivalent plain tube in the same material and wall gauge, which however is equivalent to purchasing a portable PC on its sticker price per kilogram of weight irrespective of performance. For low finned tubes, sometimes it is suggested to compare them on a ($/m^2)/m) basis, i.e. unit cost per meter of surface area per unit length. Since a low finned tube often has about 3 times the external surface area of a plain tube, if it costs 1.5 more per meter than a plain tube (a typical rule-of-thumb value), then the real cost is about one-half that of a plain tube on this surface area basis. A more realistic comparison would be to look at the respective cost per meter of tubing divided by the overall heat transfer coefficient for the optimized units, which gives a cost to performance ratio. This approach includes the entire thermal effect of internal and external heat transfer augmentation and fouling factors in the evaluation. Yet another basis is to compare the total cost of the tubing for each type of unit, since that is what the fabricator actually pays for the tubing. Even so, this is still not a realistic evaluation since a large savings in the exchanger's shell, heads, tubesheets, and fabrication costs are gained by going to a more compact unit. Overall, the best choice is to get competitive bids from the heat exchanger fabricator on the conventional plain tube unit and on the enhanced tube unit, both optimized for the application. Typical savings will be from 15–40 % even when the total tubing costs are identical. If we assume that (i) tubing, (ii) all other materials plus fixed costs and (iii) manpower each contribute equally (1/3 each) of the total cost of the heat exchanger, it is easy to see that very significant savings are gained from the second and third category as the heat exchanger gets smaller in size. Thus, the best simple economical yardstick to apply to the comparison is that of size reduction, i.e. if an enhanced unit uses 1/3 less tubes it will cost 1/3 less than the conventional unit, including the higher price per meter of the enhanced tubing. This is typically quite close to reality and easy for the thermal designer to evaluate himself.

2.3 THERMAL DESIGN AND OPTIMIZATION CONSIDERATIONS

One of the first questions about enhanced tubes to be asked is *When can I use them?* Continuing the discussion above, an old rule of thumb says that an augmentation should be considered when that fluid's thermal resistance is three times that of the other fluid. However, because doubly-enhanced tubes are readily available, i.e. those augmenting both the tube-side and the shell-side processes, almost any application can benefit thermally, and this old rule of thumb is really now only old technology. Hence, it is important to determine which augmentation(s) are applicable to the situation and then to run some simulated heat exchanger designs to determine the magnitude of the benefit in reduced size (and cost if possible) of the heat exchanger.

An important point to remember is that using an enhancement on one side of the tube will have a *positive* effect on the other side. For instance, in boiling processes an augmentation applied to the heating fluid tube surface will increase the heat flux in the smaller enhanced unit and thus the boiling heat transfer coefficient on the other side of the tube wall (which is positively effected by the larger heat flux) while also reducing the number of tubes that increases the mass velocity (and convective heat transfer) too. In single-phase applications, an augmentation will reduce the size of a new heat exchanger and thus increase the fluid velocity on the other side of the tube. This "free" enhancement is often overlooked unless a thermal design is performed for the enhanced tube unit. This *secondary augmentation* often contributes to a notable fraction of the reduction in unit size.

Another important point to remember... do *not* impose unnecessary or unwitting design restrictions on an enhanced tube heat exchanger. Compared to an optimized plain tube unit for the same application, the enhanced tube exchanger will almost always optimize to a different bundle configuration, such as shorter tube length, fewer tubes, perhaps choice of a different tube diameter, fewer tube passes, fewer bundles in parallel, etc. Thus, do not self-impose unnecessary restrictions on an enhanced unit's design.

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