Heat Exchangers

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HEAT EXCHANGERS

PREFACE TO THE ENGLISH EDITION

The production of an English translation of my book *Wärmeübertrager* was suggested by Jerry Taborek, formerly director of Heat Transfer Research Inc. (HTRI) in Alhambra, California. He was a visiting scientist in our laboratory in Karlsruhe in 1986–1987 as a Humboldt fellow when I was writing the German text, which was published in Sept. 1988 by Georg Thieme Verlag Stuttgart, New York.

In February and March 1989, I was at the Indian Institute of Technology (IIT) in Madras as a guest professor and used material from the book for my lectures there. Vijay R. Raghavan, Professor and Head of the Heat Transfer and Thermal Power Laboratory at IIT Madras, kind and generous host in those days, dear friend in the meantime, has shown keen interest in the contents of these lectures. He even expressed a desire to translate my book.

In October 1989, when the Hemisphere Publishing Corporation actually approached the German publisher for a license to produce an English edition, I wrote to Prof. Raghavan to inquire if he would assist me in the translation, to which he readily agreed. The first draft of my very crude translation took the form of some 11 notebooks, which were sent to Madras between Dec. 1989 and Feb. 1990. He sent me back the corrected notebooks one by one, with my crude draft turned into readable clear English. In the process of translation, the book has also undergone a technical review, so much so that the English version has turned out to be practically an improved second edition.

I have also incorporated results from recent papers that appeared after the publication of the original (references [B3a], [B3b], [R4]) and from an old paper which has been brought to my attention only recently (reference [K4]; see also the new Appendix C).

The notation used in this book is essentially the same as that recommended for the International Heat Transfer Conferences and used in the Heat Exchanger Design Handbook (HEDH) [H3] since 1983. Hopefully, English-speaking heat transfer engineers have become accustomed in the meantime to find *heat transfer coefficients* denoted by α (lowercase Greek *alpha*) in place of *h;* one good reason for this change is the internationally well-established use of *h* for specific enthalpy. HEDH, nevertheless, has retained the traditional (English) notation *U* for overall heat transfer coefficients, in spite of its parallel use for internal energy. In this book the symbol for *the overall heat transfer coefficient* is *k,* which is also recommended internationally as an alternative to *U,* but not widely used so far, probably because *k* has been conventionally used for the *thermal conductivity,* now internationally denoted by a λ (lowercase Greek *lambda*). In case of doubt, a look on the list of symbols, page 197, should help avoid confusion.

In addition to expressing my deep gratitude to all those who encouraged, suggested, and produced this English edition, I would like to express my hope that the book might be useful for those studying and for those professionally working in the field of heat transfer and heat exchanger design.

Karlsruhe, Winter 1990 *Holger Martin*

PREFACE TO THE GERMAN EDITION

For many engineers, *Wärmeübertrager* (literally ‘‘heat transmitter’’) in place of *Wärmeaustauscher* (‘‘heat exchanger’’) may still be a somewhat unfamiliar term for the appliance in which heat is transmitted steadily from one medium having a higher entrance temperature to another medium with a lower entrance temperature. Thermodynamicists such as Ernst Schmidt, had already used the more correct expression (i.e., *Wärmeübertrager*) in preference to the currently used one (i.e., *Wärmeaustauscher*) [S5]. Now that the VDI-Wärmeatlas [V1] too has replaced *Wärmeaustauscher* by *Wärmeübertrager* since 1984, it seems appropriate to use this term generally in engineering education.

The present book is addressed to students of engineering and science, especially in the fields of technical chemistry, chemical and process engineering, mechanical engineering, and physics. Knowledge in mathematics, thermodynamics, heat and mass transfer, and fluid dynamics, as usually obtained in universities or institutes of technology after three years of studies, are thought to be a prerequisite.

The subject of the book is not heat transfer but its application to the calculation of temperature profiles, especially the outlet temperatures of both media and the transfer performance of heat exchangers.

In Chapter 1, three examples illustrate in detail how to apply the fundamentals of thermodynamics, heat transfer, and fluid dynamics for a systematic analysis of the phenomena in heat exchangers. The systematic procedure for the solution of problems in this field is set out in the form of a comprehensive scheme.

Chapter 2 is dedicated to the influence of flow configuration on the performance of heat exchangers. Here the equations to calculate mean temperature difference and efficiency for stirred tank, parallel, counter- and crossflow, and their combinations are derived and put together in a very compact way. In some cases, short computer programs are given to evaluate more complicated formulas or algorithms. Therefore, the book should also be useful to practicing engineers as a reference for these relationships. It is so written as to enable one to work through the contents alone with appropriate preparatory training.

The fully worked-out examples in Chapter 3 are intended to show the application of the fundamentals to thermal and hydraulic design, i.e., sizing of heat exchangers. Mechanical design, with choice of material and calculation of strength according to relevant construction codes, has not been included. The latter is the subject of the course "*Konstruktiver Apparatebau,*" for which a similar book would be desirable.

The present book was developed as a text on the basis of the course "*Kalorische Apparate A,*" offered for many years at the University of Karlsruhe by Professor Dr.-Ing. Dr.h.c.INPL Ernst-Ulrich Schlünder, which I have taken over from the winter term of 1986–1987. It was Prof. Schlünder who suggested that I write this book. The entire conception and a majority of the examples are engendered by his ideas. Apart from the elaboration of the hitherto handwritten course notes, my own contribution was restricted to the more recent research results on plate and spiral plate heat exchangers, which are mainly based on the work of my former student Dr.-Ing. Mohamed K. Bassiouny as well as on the compact representation of the most important analytical results on the influence of flow configuration on heat exchanger performance developed at the end of Chapter 2. To the original course contents, I have added the analysis of heat exchangers coupled by a circulating heat carrier in order to assist the reader in comprehending the phenomena in a regenerator. All the numerical examples have been reworked, using the calculation procedures for heat transfer coefficients and friction factors currently recommended in the pertinent handbooks on the subject.

Dr.-Ing. Paul Paikert, director of the Research and Development Department of GEA Luftkühlergesellschaft, provided field data for the design examples on plate and shell-and-tube heat exchangers, which is gratefully acknowledged. I would also like to thank my former colleague Dr.-Ing. Norbert Mollekopf, now with Linde A.G., for information on the design of regenerators and other heat exchangers in flue gas cleaning processes applied in power plants. To my colleague Akad. Dir. Dr.-Ing Volker Gnielinski, I am indebted for his critical inspection of the manuscript and for many a valuable hint on the layout of the book. For the excellent drafting of a majority of the figures, I would like to thank Lothar Eckert and Pedro Garcia. Some of the figures have been obtained courtesy of Linde A.G. (Höllriegelskreuth) and W. Schmidt G.m.b.H. u. Co. K.G. (Bretten). I have myself produced some of the figures, using the graphic software "MacPaint" by Apple Inc.

Finally, I would like to thank Nana very much for carefully transcribing my handwritten notes into neatly typed text stored on a disk. She sacrificed many a weekend for this arduous work.

Karlsruhe, Summer 1988 *Holger Martin*

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CHAPTER

ONE

ANALYSIS OF SOME STANDARD TYPES OF HEAT EXCHANGERS ON AN ELEMENTARY BASIS

1. STIRRED TANK WITH JACKET

1.1 Description

The stirred tank, or stirred vessel, is one of the simplest and, at the same time, most versatile types of apparatus used in process engineering. In the model shown in Fig. 1.1, the vessel is put together from cylindrical, annular, and spherical shell segments according to structural analysis. The lower part has a double-walled construction with inlet and outlet headers, so that the contents of the vessel may be heated or cooled by a medium flowing through the jacket. In Fig. 1.2, this apparatus is drawn schematically with its most important functional features. The flows of mass and energy entering and leaving the vessel and the jacket are inserted into the sketch as arrows and denoted by symbols, such as $\dot{M}$ for mass flow rate, $\dot{Q}$ for heat flow rate, and $\dot{W}$ for stirrer power, which are, if necessary, identified by subscripts for position, time, or state.

1.2 Formulation of Questions

In the next step, one has to become clear on the questions of which are exactly the unknown and which are the given—or, at least, to-be-fixed-in-advance—quantities. Reasonable questions in connection with heating a liquid in a stirred tank may be , for example,

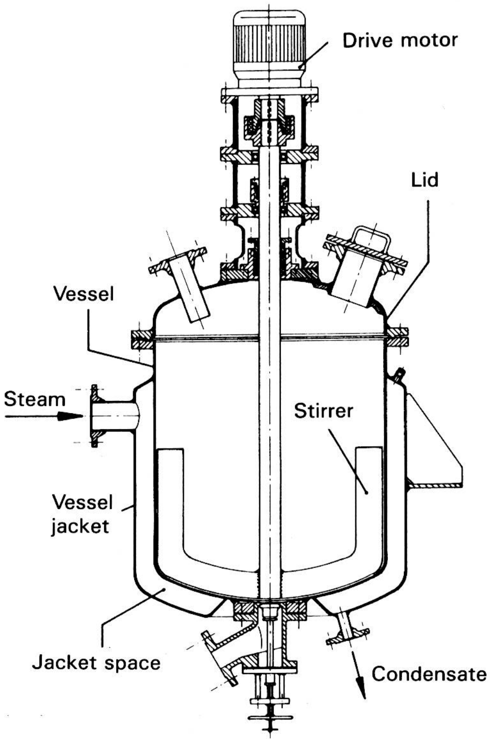

Figure 1.1 A stirred tank with jacket.

a. How does the temperature of the contents of the vessel change with time after the steam inlet valve has been opened?
b. What is the consumption of heating steam?
c. What is the influence of the stirrer speed on the heating process?

To answer these questions, some quantities have to be known or fixed in advance. Only in the course of the analysis will it become apparent that, to answer the question, we need the vapor pressure p_V and, thus, the condensation temperature $T_V = T^*(p_V)$ of the vapor in the jacket, mass M and initial temperature T_I of the liquid in the vessel, type and rotational speed of the stirrer, and other parameters. In any case, it will be useful to list all necessary parameters using unambiguous symbols. Question (a), for example, can be formulated in symbolic writing as

$$T = T(t, \text{parameters})$$

Here T, the unknown (or sought-after) quantity, the temperature of the liquid in the tank, is a function of the time t after the steam inlet valve has been opened and "parameters" contain all other quantities that have to be known *a priori* to calculate the function $T(t)$. In general, before starting the formal symbolic analysis, one has to be clear on the following questions:

- Which is the quantity sought after?
- What does it mainly depend on?
- Which other parameters are needed?

1.3 Application of Physical Laws

To answer the question posed in the previous section, in general, three classes of physical laws are at our disposal: the laws of conservation (of mass, momentum, energy); the laws of equilibrium; and the rate equations (kinetics of transport processes).

Over a space, thought of as the "control volume," one may write a balance for physical quantities that obey a law of conservation. Thus, the mass balance for the steam jacket is

$$\dot{M}_V - \dot{M}_C = \left(\frac{dM}{dt}\right)_{\text{in the steam jacket}} \tag{1.1}$$

If the vapor pressure p_V remains constant and if, by means of a steam trap, the liquid level of condensate in the jacket is also kept constant, then the change of mass (of

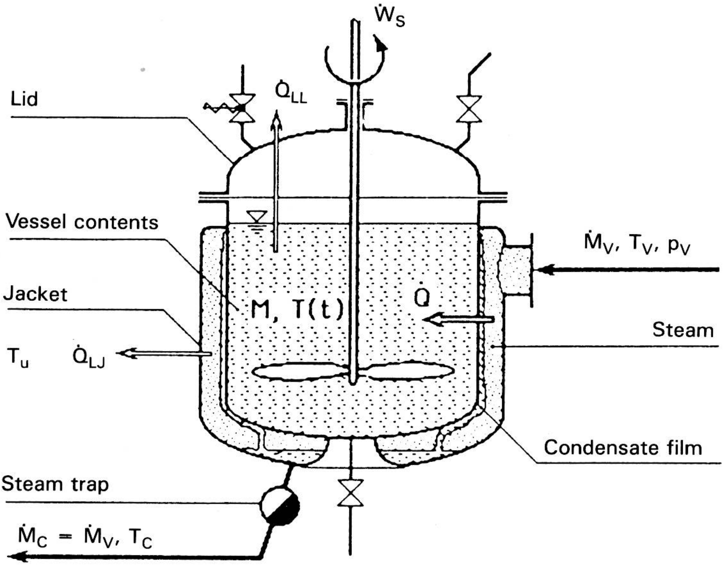

Figure 1.2 Stirred tank: sketch, streams, symbols.

vapor and condensate) in the jacket with time is equal to zero. The amount of vapor flowing in is always equivalent to the amount of condensate led off ($\dot{M}_V = \dot{M}_C$). The corresponding energy balance for the steam jacket reads:

$$\dot{M}_V \Delta h = \dot{Q} + \dot{Q}_{LJ} \tag{1.2}$$

Here $\Delta h = h_V - h_C$, the difference of the specific enthalpies of vapor and condensate, i.e., the enthalpy of vaporization $\Delta h_V(T_V)$ and appropriate additional enthalpy differences in case of steam entering superheated and condensate leaving subcooled. $\dot{Q}$ is the rate of heat transferred from the condensing steam to the contents of the vessel, while $\dot{Q}_{LJ}$ is the heat "loss" from the jacket to the surroundings. In order to answer the question 1.2 (a) for the variation with time of the temperature of the contents of the vessel, we have to regard the contents as a system. In case both inlet and outlet valves remain closed, the energy balance for the liquid contents of the vessel is:

$$\dot{Q} + \dot{W}_S - \dot{Q}_{LL} = \left(\frac{dE}{dt}\right)_{\text{Vessel contents}} \tag{1.3}$$

$\dot{W}_S$ denotes the power transferred by the stirrer and $\dot{Q}_{LL}$ the heat loss from the contents through the lid to the surroundings. In this case (and similarly in many other practical cases in heat exchangers), of the components of the total energy of the system, i.e., the potential, kinetic, and internal energies, only the internal energy U changes. On the other hand, one has to take into account the expansion or contraction of the fluid in the vessel when heated or cooled under constant pressure. Thereby it transfers power by change of volume $\dot{W}_V = p(dV/dt)$ to its surroundings, which has to be subtracted from the left hand side of eq. (1.3)

$$\dot{Q} + \dot{W}_S - \dot{Q}_{LL} - \dot{W}_V = \left(\frac{dU}{dt}\right)_{\text{Contents}} \tag{1.4}$$

By introducing the enthalpy

$$H = U + pV \tag{1.5}$$

the energy balance can be simplified for constant pressure:

$$\dot{Q} + \dot{W}_S - \dot{Q}_{LL} = \left(\frac{dH}{dt}\right)_{\text{Contents}} \qquad (p = \text{const}) \tag{1.6}$$

Since the pressure in heat exchangers often remains constant with time, the energy balance can be formulated most conveniently in many cases as in eq. (1.6) with the change of enthalpy dH/dt on the right hand side. When rewriting eq. (1.6), the laws of equilibrium thermodynamics, i.e., the second class of physical laws, have already been used. Further, the enthalpy H may be expressed in terms of the temperature T (for constant pressure):

$$dH = d(Mh) = c_p\, d(MT) \tag{1.7}$$

eventually leading to

$$\dot{Q} + \dot{W}_S - \dot{Q}_{LL} = \left(Mc_p \frac{dT}{dt}\right)_{\text{in the vessel}} \tag{1.8}$$

for constant mass of the contents of the vessel with $T(t = 0) = T_I$.

The question regarding the variation of temperature with time, however, can not yet be answered with this equation alone. Apart from the laws of conservation and equilibrium, one needs the rate equations, i.e., one needs statements on the dependency of the fluxes on the field variables, such as the temperature, the flow velocity, and the concentration. These laws are always formulated in such a way that the fluxes vanish when approaching equilibrium. In the simplest version, the fluxes are taken as linearly related to the departure of the state variables from their equilibrium values. Should the steam in the jacket be in thermal equilibrium with the fluid in the vessel, then its temperature T_V would have to be equal to the temperature T of the vessels contents and vice versa:

$$T_{V,\text{Equilibrium}} = T \tag{1.9}$$

or

$$T_{\text{Equilibrium}} = T_V \tag{1.10}$$

$$\dot{Q} = K(T_V - T_{V,\text{Equilbrium}}) \tag{1.11}$$

The factor of proportionality K is thereby usually subdivided into two or more factors:

$$\dot{Q} = kA(T_V - T) \tag{1.12}$$

A is the transfer surface area, in this case, the surface area of the wall of the vessel, which is equipped with the jacket. The area specific proportionality factor $k = K/A$ is called "overall heat transfer coefficient." Analogous to eq. (1.12) one can write the rate equations for the heat losses in eqs. (1.2) and (1.3):

$$\dot{Q}_{LJ} = (kA)_{LJ}\,(T_V - T_a) \tag{1.13}$$

$$\dot{Q}_{LL} = (kA)_{LL}(T - T_a) \tag{1.14}$$

Since the streams are vectors, one has to exercise due care that their direction is always the same in the balance and in the corresponding rate equation. If the power of the stirrer $\dot{W}_S$ is known, e.g., kept constant by an appropriate control, the question posed under (a) in section 1.2 can be answered from the combined application of