Two-Phase Flow Heat Exchangers

Thermal-Hydraulic Fundamentals and Design

Edited by

S. Kakaç, A. E. Bergles and E. O. Fernandes

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edited by

Sadık Kakaç

Department of Mechanical Engineering,
University of Miami, Coral Gables, Florida, U.S.A.

Arthur E. Bergles

Department of Mechanical Engineering,
Rensselaer Polytechnic Institute, Troy, New York, U.S.A.

and

E. Oliveira Fernandes

Department of Mechanical Engineering,
University of Porto, Porto Codex, Portugal

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PREFACE

Two-phase flow heat exchangers are vital components of systems for power generation, chemical processing, and thermal environment control. The art and science of the design of such heat exchangers have advanced considerably in recent years. This is due to better understanding of the fundamentals of two-phase flow and heat transfer in simple geometries, greater appreciation of these processes in complex goemetries, and enhanced predictive capability through use of complex computer codes. The subject is clearly of great fundamental and practical importance.

The NATO ASI on Thermal-Hydraulic Fundamentals and Design of Two-Phase Flow Heat Exchangers was held in Povoa de Varzim (near Porto), Portugal, July 6-17, 1987. Participating in the organization of the ASI were the Department of Mechanical Engineering and the Clean Energy Research Institute, University of Miami; Universidade do Porto; and the Department of Mechanical Engineering, Aeronautical Engineering, and Mechanics, Rensselaer Polytechnic Institute. The ASI was arranged primarily as a high-level teaching activity by experts representing both academic and industrial viewpoints. The program included the presentation of invited lectures, a limited number of related technical papers and discussion sessions.

The program, as reflected in the contents of this volume, was divided into two parts: background and thermal-hydraulic fundamentals, and heat exchanger design and practice. The first part includes comprehensive reviews of heat transfer for boiling and condensing as well as single-phase flows. Included are augmentation; instabilities, and fouling. The second part features extensive discussions of experience with fossil boilers, nuclear steam generators, process evaporators, condensers, gas-solid heat exchangers; compact heat exchangers, and cooling towers.

We express our appreciation to the organizations for supporting our involvement with the organization of the ASI. Our special thanks go to the invited lecturers and co-authors: D. Butterworth, J.G. Collier, M. Cumo, L. Friedel, P. Hawkins, M. K., Jensen, B. Kılkış, J. B. Kitto, W. Koehler, P. J. Marto, F. Mayinger, L. Melo, J. Merz, R. Oskay, M. B. Pate, E. Paykoç, R. K. Shah, E.R.C. Somerscales, J. Taborek and H. Yüncü.

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Finally, our heartful thanks are extended to the unmentioned participants for their attendance and involvement in the discussions that contributed so much to the success of this Advanced Study Institute.

Every effort has been made by the editors to minimize typographical errors and language corrections. But, it is impossible in a work of this magnitude to achieve an error-free publication. Therefore, the articles in this volume have been judged and accepted on their scientific quality, and in some cases language corrections may have been sacrificed in order to allow quick dissemination of knowledge to prevail.

S. Kakaç
A.E. Bergles
E.O. Fernandes

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Part I. Thermal-Hydraulic Fundamentals

CLASSIFICATION AND APPLICATIONS OF TWO-PHASE FLOW HEAT EXCHANGERS

F. MAYINGER

Lehrstuhl A für Thermodynamik
Technische Universität München
Munich, Federal Republic of Germany

ABSTRACT

Approximately 60% of heat exchangers in industrial use are working in a two-phase flow mode. They are used in the power and process industry as well as in air conditioning, in refrigerating, and in food production. Mostly the latent heat of evaporation of a vapour-liquid mixture is used to improve the transport capacity and also to enhance the heat transfer process.

After discussing different criteria and possibilities classifying two-phase flow heat exchangers, their design and application, some examples of modern design in heat exchangers with phase change, are presented. Finally thermo- and fluiddynamic phenomena are briefly discussed which have major influence on the design and the operational performance of two-phase flow heat exchangers.

The paper intends to give an introduction to the following lectures and papers dealing with the design of special two-phase flow heat exchangers and their heat transfer calculation in detail.

1. INTRODUCTION

The oldest two-phase flow heat exchanger used by mankind was certainly a cooking-vessel for preparing meal by boiling. One of the probably first two-phase flow heat exchanger for "public" use was proposed by Archimedes who invented a "steam-gun" for shooting bullets. Archimedes enclosed water in a tube, heated this water and water-vapour mixture, and finally untied the bullet being arrested on one side of the tube. This, perhaps, was the first industrialized use of a two-phase flow heat exchanger of military character proving the old Roman proverb: "War is the father of many things".

A little later Heron invented the "turning-sphere" which was fed by a boiler, one of the first two-phase flow heat exchanger design too. The boiler had, as fig.1 shows, the shape of a cooking-vessel of that time, i.e. no special design deliberations were performed. The steam produced in the "heat exchanger" - the cooking vessel - flowed via a short vertical pipe into a sphere which was put in rotation by the momentum of the steam jet leaving this sphere via two nozzles. Heat was added to the heat exchanger by a wood or coal fire.

In ancient Egypt boiling heat transfer is reported to have been used for producing alcohol via destilling wine. There is no drawing how this evaporator looked like. The use in food-production was the dominant application of two-phase flow heat exchangers until the beginning of the industrial age, when James Watt invented his steam engine and chemical engineering started. From this time on a vigorous development in two-phase flow heat exchangers began continuing until today.

S. Kakaç et al. (eds.), Two-Phase Flow Heat Exchangers, 3–27.

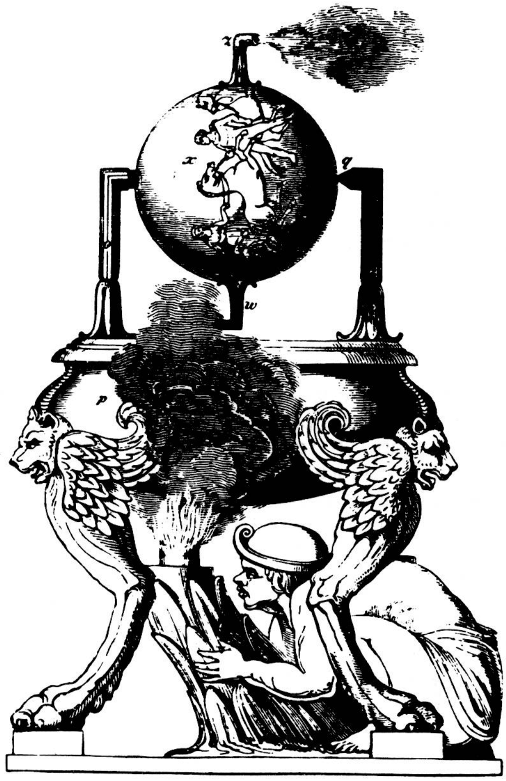

Fig.1: "Turning sphere", quoted by Hero of Alexandria, 120 b.c.

Mostly the benefits of phase change, namely the latent heat of evaporation and high heat flux densities were attractive to the designers of heat transport components but also the need to produce vapour, for example for a steam engine, or to separate a condensible component out of a gas mixture were reasons for engineers in the power- and process-industry to design and construct evaporators and condensers. In the chemical industry the function of an evaporator is to evaporize a liquid or to concentrate a solution by vaporizing part of the solvent. Sometimes this vaporizing goes to the point at which crystallization occurs. Then even a three-phase mixture may be present in such a heat exchanging apparatus. Vaporizing may start from rigid surfaces heated by a hot fluid from the other side or by radiation heat transfer but also on flexible surfaces, for example on a liquid-vapour interface, when a hot liquid is depressurized and flashing occurs.

Condensate may form from vapour in a number of different ways. Usually there is filmwise condensation on a rigid wall. Dropwise condensation would allow much higher heat flux densities, but this is difficult to maintain contineously in heat exchangers. The vapour, however, can condense also out of a gas phase directly forming droplets suspended in the gas. Finally when vapour is brought directly into contact with a cold liquid, so-called direct contact condensation occurs.

For a systematic classification of two-phase flow heat exchangers however, we need a much more detailed view of the different possibilities of flow configurations, design aspects and application purposes.

2. CLASSIFICATION OF TWO-PHASE FLOW HEAT EXCHANGERS

Heat exchangers may be classified according to many different aspects and features. Shah /1/ proposed classifications according to the transfer processes, degree of surface compactness, construction features, flow arrangements, number of fluids, and heat transfer mechanisms. From the various possible criteria of classification, shown in a little different arrangement in fig.2, we will only discuss

Classification Criteria of Heat Exchangers

I. **Transfer Process**
II. **Construction**
III. **Flow Arrangement**
IV. **Heat Transfer Mechanisms**
V. **Number of Phases or Fluids**
VI. **Application**

Fig.2: Classification Criteria for heat exchangers

the classification criteria according to heat transfer mechanisms, construction and application. Transfer processes according to Shah /1/ are direct contact or indirect contact for transporting the heat. In a direct contact type heat is transferred through direct contact between the hot and cold immiscible fluids, for example by condensing vapour in liquid. However, one of the fluids can also be a gas and the other one a very low vapour pressure liquid. A water cooling tower with forced or natural draft or flow is the most common application of direct contact heat exchangers. Here, however, we have to notify that more than 90% of the energy transfer is by virtue of mass transfer and heat transfer has much a minor mechanism.

In this paper, however, we shall mainly or only discuss indirect contact heat exchangers. Classifying heat exchangers in general according to their heat transfer mechanisms we can distinguish, as briefly outlined in fig.3, between single-phase convective heat transfer, heat transport due to phase change and heat transfer by radiation. According to this classification only the phase change mode of heat transfer is of interest here. Again, generally speaking, we would habe to differentiate

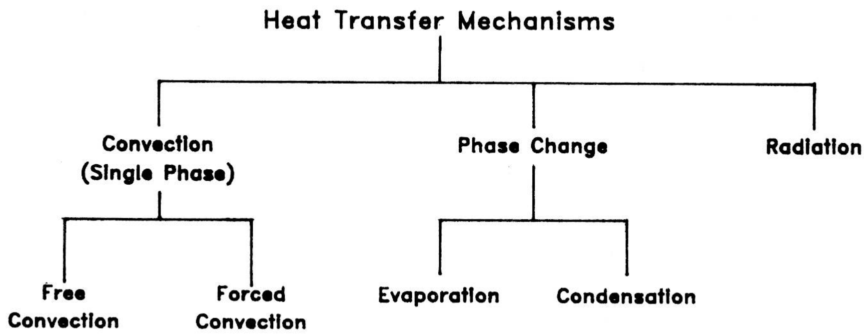

Fig.3: Classification of heat exchangers according to heat transfer mechanisms

between evaporation, condensation, sublimation, and de-sublimation. The later two heat transfer mechanisms, i.e. the direct change between gaseous and solid phase, play no role in technical and industrial heat transport.

However, also without phase change we may have a two-phase flow heat transfer mode. This is for example the case in fluidized beds where a mixture of gas and solid particles is transporting heat to or from a wall which may have the form of a cylinder or of a flat plate. This fluidized bed heat transfer mechanism became recently very timely in power engineering with the development of fluidized bed combustion. Tube bundles are there immersed in the fluidized bed of coal particles, ashes, and hot gas. Inside these tubes another type of two-phase flow exists, namely a liquid/vapour mixture.

From a design point of view the classification of heat exchangers occurs much more detailed (fig.4) Many design concepts are used as well in two-phase

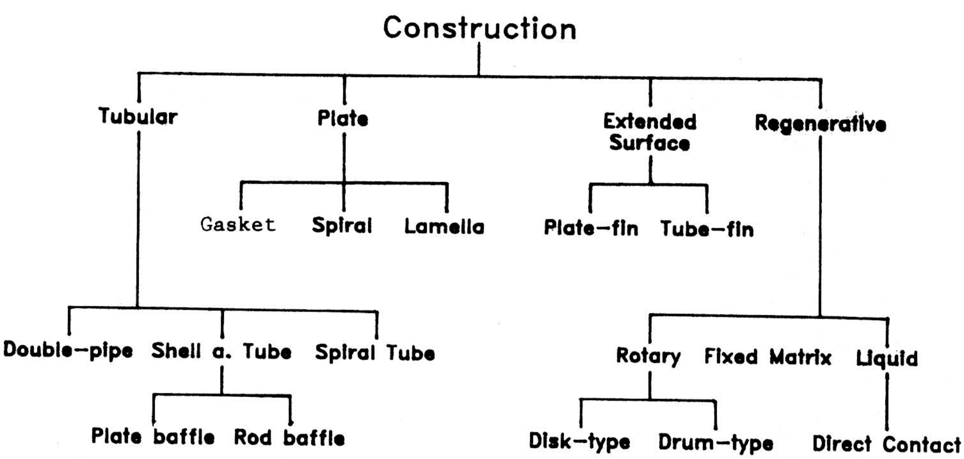

Fig.4: Classification of heat exchangers according to construction (R. Shah /1/)

mode as in single-phase one. From a pure geometrical point of view we can distinguish between a tubular- and a plate-design. However, we can also subdivide the walls transferring the heat in extended and in non-extended surfaces. As well known extended surfaces, like fins, are used in the tubular- as well as in the plate-arrangement, if the heat transfer coefficient is low.

Finally we have to consider whether the heat from the hotter fluid is transfered instantaneously to the colder one or whether it is stored for a while before it can heat up the colder fluid. Heat exchangers with this storage step in between are called regenerators. Two-phase flow heat exchangers are very rarely operated in a regenerative mode.

Two-phase flow heat exchangers are of tubular- and of plate-design. Small tubular units have a double-pipe arrangement. The larger ones are designed as shell- and tube apparatus. With plate-heat exchangers we find the gasket and the lamella design. With condensation of vapour substances having low latent heat of evaporation extended surfaces with fins on tubes or plates are used.

Examples of evaporators with tubular design are shown in fig.5. This standard

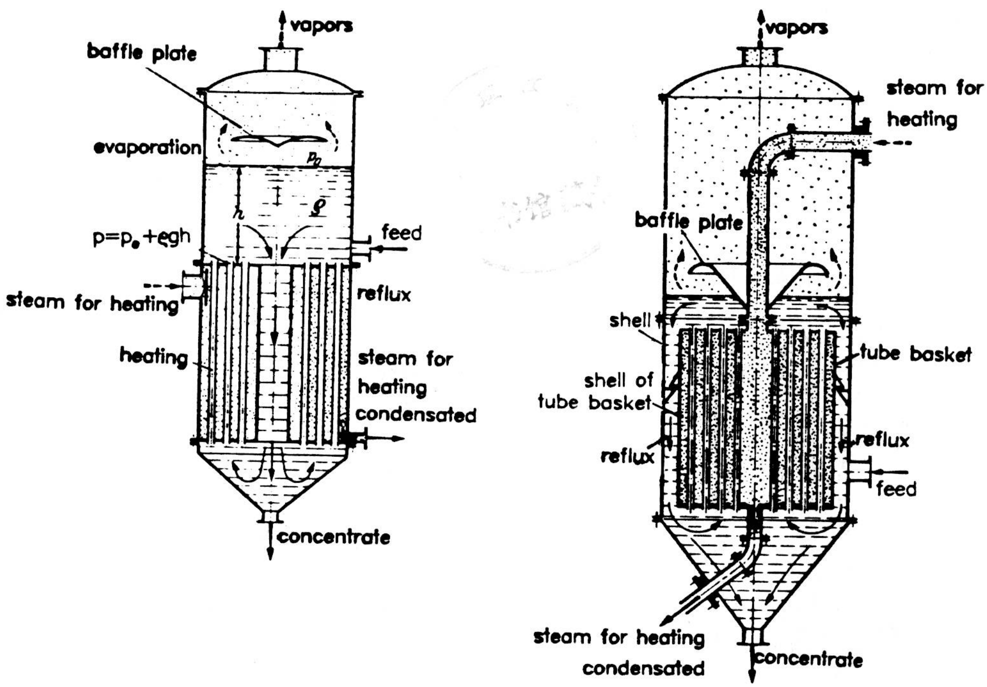

Fig.5: Evaporator with internal and natural circulation, (a., short tube bundle with central reflux, b., basket with annular reflux)

design is frequently used in the chemical industry for concentrating solutions by vaporizing the higher volatile components. The soluble mixture is in a cylindrical vessel which contains a tube bundle in its lower part. These tubes are heated from the outside by condensing steam. The soluble mixture is vaporizing and rising inside