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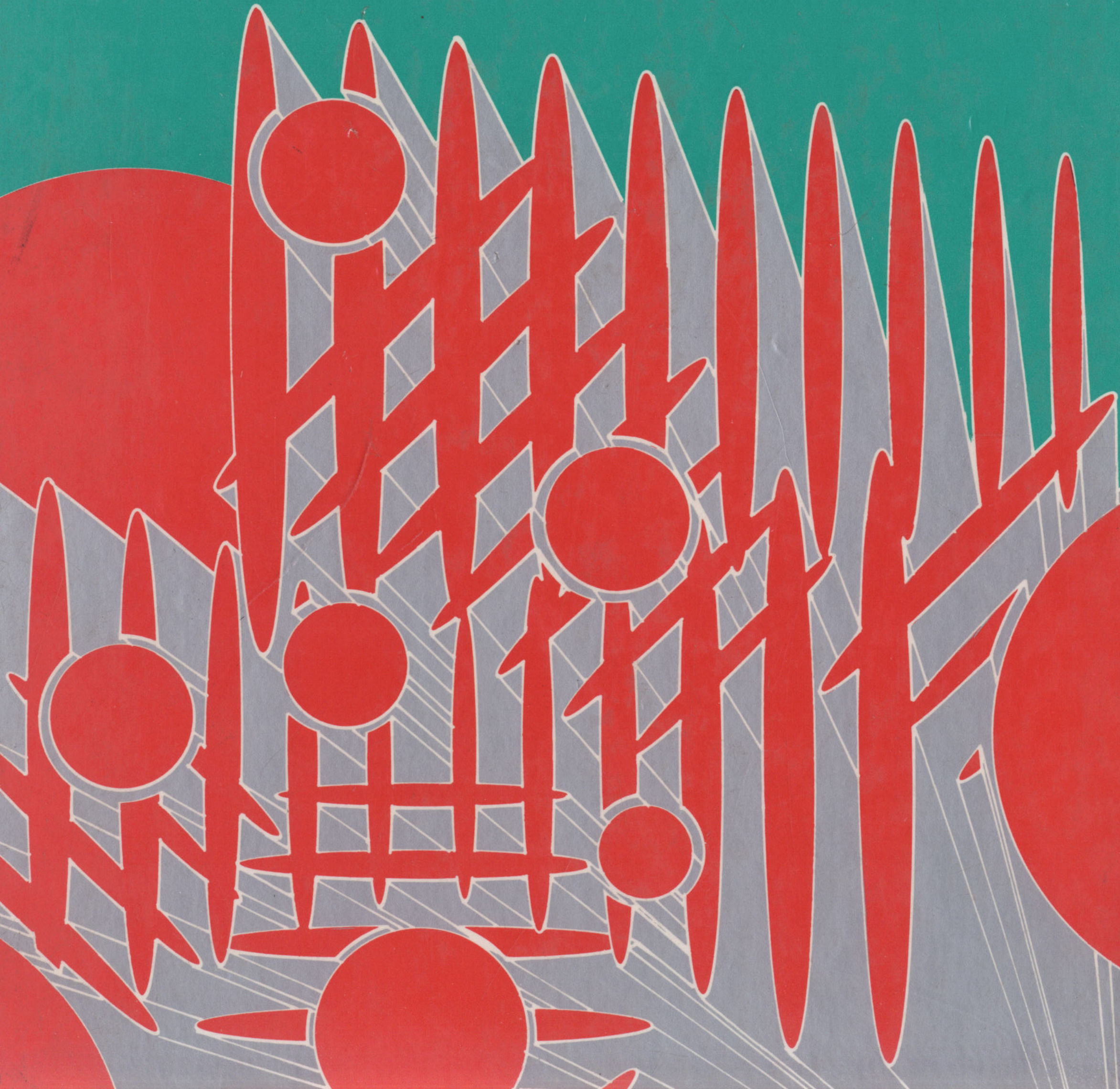
HEAT EXCHANGE ENGINEERING

volume 1
design of heat exchangers

E. A. Foumeny and P. J. Heggs



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Volume 1
Design of Heat Exchangers

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PREFACE

Since the oil crisis of 1973, the developed countries of the world have become more conscious of their energy requirements. In fact, with heightened concern for energy conservation, there has been a substantial increase in research activities, as many investigators continue to seek ways of improved design and performance. New or refined design of thermal systems would, no doubt, benefit U.K. industry, whose annual heat transfer equipment expenditure stands at around £200 m.

This volume in the series on Heat Exchange Engineering is designed to provide valuable information on the design aspects of thermal systems.

Heat Exchanger Design is a process to create equipment to accomplish the desired thermal changes. The choice of the configuration is generally influenced by the allowable pressure drop, mechanical and cost considerations as well as the operational flexibility of the available systems. Undoubtedly the most important factor in the correctness of the final design is associated with the accuracy of the design information. The literature on the basic correlations is enormous but one may also discover that there are substantial gaps and inconsistencies in the published data for both existing and newer geometries. Multitubular systems, plate heat exchangers and thermal regenerators are typical examples where such deficiencies are clearly evident. These shortcomings can be rectified by extensive experimentation supported by descriptive mathematical models of the system in question.

However, an important part of the current design approach in achieving enhanced heat exchangers is what is being called process intensification. Basically, it is concerned with the philosophy of reducing the size of the equipment, not just to minimise capital cost but also to facilitate improved operational flexibility.

We would like to thank all those who have contributed to this volume and acknowledge especially Mr. Ellis Horwood, our publisher for his support and advice throughout the stages of preparation of the manuscript. Thanks too must go to the East Pennine Centre of the Institution of Chemical Engineers and the Energy Efficiency Office for their support. Many thanks to Judith Squires for her excellent work in typing the manuscript. Last, but by no means least, thanks must go to our wives Mahboubeh and Carole for their patience and endless support during the course of preparing and editing this volume.

E. A. Foumeny and P. J. Heggs

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Chapter 1

SHELL AND TUBE ARRANGEMENTS FOR MULTITUBULAR REACTORS

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I INTRODUCTION

Multitubular reactors (MTR) are usually used for highly exothermic reactions where temperature control is necessary to ensure good selectivity and yield. Temperature control is achieved by circulating a coolant around a tube bundle to remove the heat released by chemical reaction. The general mechanical arrangement is an assembly of tubes inside a shell, basically of the same form as the shell and tube heat exchanger. However, the operational characteristics are usually quite different and necessitate not only refinements in the mechanical design but different operational policies. Most MTRs require many tubes in order to meet the production rate: also higher heat transfer duties have to be met. Because of the high sensitivity of the reaction rate to temperature, the arrangements for routing the coolant flow can have an important effect on the reactor performance and hence a strong influence on the design as well as the operational policy.

Heat exchanger designs have been based on a combination of both theoretical and experimental studies of equipment (Gunter, Sennstrom and Koop, 1947; Gupta, 1956, Gay and Roberts, 1970; Berner, Dust and McEliot, 1984; Murray, 1988). Applying these results directly to reactors is not appropriate because no account has been taken of the heat generation inside the tubes which occurs in reactors. McGreavy and Maciel (1988) have given examples of the problems which can arise if the reactor is treated simply as a heat exchanger. It can result in unstable operation with very low conversion efficiency. A systematic study is needed to identify how internal system interactions arise in the reactor so that adverse effects can be minimized. The objective of this study is to explore these aspects in more general terms.

An important first step is to develop detailed models of both the shell and tube-side which account for all phenomena which are likely to be important. Only when this information is available is it possible to gain the necessary insight into the preferred arrangements for the tubes in the reactor. This then forms the basis for a search for improved performance while preserving stable operation. The strategy will be illustrated by reference to the partial catalytic oxidation of benzene to maleic anhydride. Further details can be found in Maciel (1989).

II ASPECTS OF THE MATHEMATICAL MODEL FOR A REACTOR

Catalytic multitubular reactors (MTR) are made up of tubes packed with catalyst pellets. The heat is generated inside the tubes as a result of the chemical reaction on the catalyst and is removed by a coolant circulating around the tubes. The mechanical constructional details are discussed in detail elsewhere (Maciel, 1989). Cross flow over the tubes is a major component but some parallel flow occurs because of leakage streams due to the annular clearances between the tube and baffle (due to manufacturing expansion clearances) as well as in the window zones. This mixed flow can have a significant influence on the performance of the reactor.

Two different domains need to be considered: the tube-side, where the heat is generated by the chemical reaction and the shell-side where the coolant absorbs the heat and controls the role of heat transfer and hence temperature distribution. There is therefore an intimate relationship between these two domains which results in internal process interactions which can give rise to operational instabilities.

A. The Tube-side

The overall reaction rate is constrained by heat and mass transfer to and in the catalyst and to account for this, a heterogeneous model is necessary. In addition, severe radial gradients may also occur so a two-dimensional (axial-radial) model for the reactor tube needs to be used.

B. The Shell-side

The coolant flow distribution is determined basically by the pressure drop of the fluid flowing through the tube bundle and so is based on a momentum balance. It is convenient to use local balances based on algebraic equations since this enable changes in the direction of the coolant flow to be handled. The domain is divided into an array of two-dimensional ideal cells with the coolant flow being split into components perpendicular and parallel to the tubes. The flow distribution is obtained by a momentum balance written in terms of flow between adjacent cells. The simultaneous equations can be solved directly with the mass balance to give the flow distribution.

Figure 1 illustrates the procedure where ‘i’ refers to the parallel and ‘j’ the cross flow. The detailed equations for the first zone are shown in the Appendix.

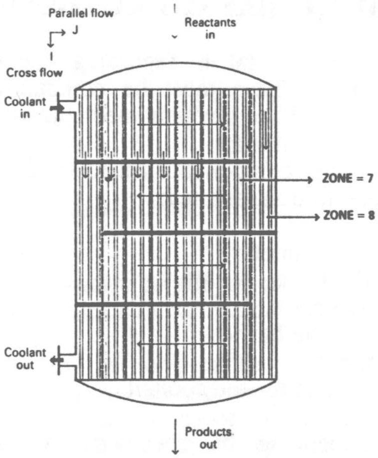

Figure 1: Schematic of a multitubular reactor i - parallel flow of coolant; j - cross flow

This discrete representation allows for consideration of the changes in the net flow area across the reactor diameter and enables different arrangements to be explored, including variation in the tube-coolant heat transfer coefficient. Other aspects of the arrangements such as tube-pitch, bundle-shell by-pass flow, distance between baffles and size of window can also be examined.

C. Numerical Solution for the Equations

Solution of the system of partial differential equations describing the tube-side can be conveniently obtained using the method of lines. Orthogonal collocation is used to discretise the radial variable and the resulting systems of ordinary differential equations in the axial direction can then be integrated simultaneously. The equations constitute a system of non-linear algebraic equations and can be conveniently solved using an algorithm combining the Newton-Raphson with step length restriction based on the Levenberg-Marquard or continuation methods (Maciel, 1989).

An important requirement in applying the solution procedure is to obtain the minimum realization of the system. In the coolant domain 4 cells are used for the cross flow and 2 cells at the entrance and exit for each zone solution procedure are given elsewhere (Maciel, 1989; McGreavy, Maciel and Castro, 1990).

The reactor considered in this study has 10460 tubes, each 3 m long. The shell diameter is 4.65 m and has window openings of 1.0 m with tubes of 0.0318 m internal diameter on a triangular tube pitch of 0.042 m. The kinetic parameters and fluid flow rates are given in the nomenclature.

III MECHANICAL CONFIGURATION

Decisions have to be taken regarding the arrangements of the mechanical components. These must be compatible with a satisfactory operational policy and conditions which meet the production schedule and satisfy all necessary safety criteria.

The following major components relate to details of the mechanical construction which need to be examined:

tube-baffle orifices diameter
arrangement of the tubes
materials of construction
number and size of the baffles
space between baffles
feed and exit positions for the coolant

Other factors influencing the mechanical construction details are the coolant physical properties since they affect the coolant flow distribution and the heat transfer conditions. The coolant physical properties and hence the choice of the coolant should be regarded design parameters and extensive study on how the coolant fluid properties can influence design has given by McGreavy and Maciel (1990).

Computer simulation can be used to explore the intrinsic characteristics of such systems and assist in understanding the nature of the interactions. Success depends on the model being sufficiently detailed to reveal all the significant features of the reactor performance, including situations where multiple states arise, (Maciel, 1989). Great care is needed to guarantee that reliable solutions are obtained before exploring the general response characteristics to find an optimal design which is both stable and robust.

Figure 2 shows typical coolant temperature patterns for a multitubular reactor operated co-currently. it can be seen that there are significant concentration and temperature changes inside the tubes. They arise as a result of the thermal interactions induced by the mechanical configuration. To improve both the reactor performance and operational behaviour the conditions in some parts of the reactor need to be changed. As already noted, the leakage through the baffles gives rise to coolant flow parallel to the tubes and this influences the heat transfer coefficients. it causes reduction in the overall heat transfer coefficient because the cross flow is reduced. As a consequence, there is less scope for adjusting the temperature distribution. It should be noted that leakage is a significant factor even when the gaps are within normal manufacturing tolerances and so need to be considered when assessing the mechanical design.

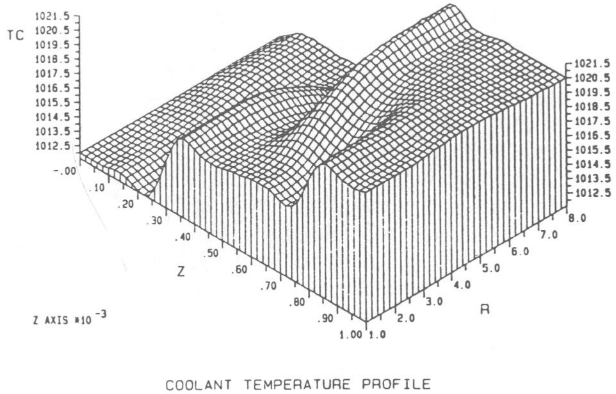

Figure 2: Coolant temperature profile for a co-currently operated multitubular reactor in the radial (R) and axial (Z) directions.

Since knowledge of the temperature distribution is very important, conduction through the baffles should also be considered. Among other things it has a bearing on the choice of baffle thickness: it can also be of relevance to the choice of materials of construction which are factors not normally considered in heat exchanger design (Rummer (1987).

Temperature profiles in the reactor tubes with baffle thickness of 0.01 m, are shown in Figure 3 and can be compared with the predictions ignoring baffle conduction (Figure 4). As the baffle thickness increases, the profiles tend towards this limiting case as would be expected. Clearly, baffles having a high thermal conductivity will promote feedback of heat, and so will result in higher temperature peaks near the feed input. The implications therefore need to form part of the preliminary appraisal of the design particularly when deciding on processing conditions.

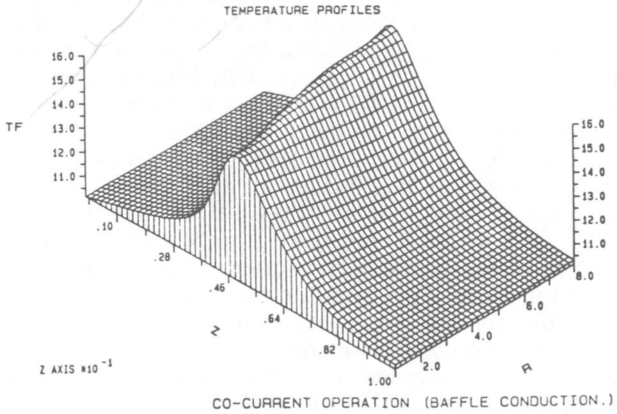

Figure 3: Tube-side temperature profiles. Baffle thickness = 0.01 m QV = 0.8 m^3/s, Tco = 675K, Tfo = 675K (Consideration of baffle conduction).

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