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CHAPTER

ONE

INTRODUCTION

1-1 PURPOSE AND TECHNICAL IMPORTANCE OF HEAT EXCHANGERS

Heat exchangers are employed to transfer heat or "cold" from one fluid to another which has a lower or higher initial temperature. For the most part, heat is exchanged between liquids or gases. In principle heat can be transferred between more than two mediums in a heat exchanger.[1]

The numerous applications of heat exchangers in industry are based upon the following consideration. Combustion processes and many other chemical reactions take place at temperatures which are much higher than ambient. The gaseous or liquid products frequently will leave a process at a relatively high temperature and therefore will still contain large quantities of heat which should not go unused in an economical operation. Conversely it is often required to preheat a material before it is processed. The best way to utilize the heat contained in the exit materials is to transfer it to the entry materials using a heat exchanger. In chemical reactions, for example in the combustion in industrial furnaces, such a preheating, usually of the combustion air, will be often indispensable since the heat of reaction alone will not be sufficient to maintain the necessary high temperatures. Such recovery of the heat contained in the exit materials from a process always increases the economy of operation. One of the oldest and best known operations of this type is the preheating of the air and the fuel gases in the regenerator of a Siemens–Martin furnace; heat is retrieved from the waste combustion gases.

The use of heat exchangers is, however, in no way restricted to the cases

[1] For more detailed considerations of the term "heat exchanger" see Sec. 1-4.

described. In Cowper stoves for blast furnaces, for example, it is not hot exhaust gases but the heat from blast furnace gas, burnt specifically for this purpose, which serves to heat the air for the furnace.

Of particular importance is the exchange of heat between gases at various pressures in low temperature technology, for example in the condensation and separation of air. Low temperatures of around −200°C and sometimes lower can neither be reached nor maintained with known methods for reducing temperature if the "cold" contained in the return gas is not transferred to the fresh, compressed inlet air in a heat exchanger.

1-2 CLASSIFICATION AND OPERATION OF HEAT EXCHANGERS

The fluids in heat exchangers do not, in general, come into direct contact with each other; if they did they would mix and the pressure gradient which generally exists between the fluids could not be maintained. Cases in which, for example, two immiscible liquids, or a liquid and a gas, or even a gas and a moving solid material exchange heat by direct contact, are relatively infrequent, except when mass transfer takes place as in rectification or evaporative cooling. Disregarding these cases then, heat transfer from one material to another requires there to be a heat conducting partition or a heat storing mass. Partitions have the dual task of guiding the fluids into *spatially divided channels* and at the same time transferring the heat over the shortest possible path. Fluids pass *simultaneously* and *continuously* through heat exchangers which have partitions. In the terminology of the iron and steel industry heat exchangers of this type are called "*recuperators*". The term recuperator also includes, however, the special case already mentioned, in which heat is exchanged between two immiscible fluids or even between a fluid and pieces of solid material. In this case the surface of the fluid or the surface of the solid material assumes the role of a partition.

Heat exchangers which contain a heat storing mass are called "*regenerators*". The heat storing mass, which is usually formed of checkerwork or is porous, has numerous, more or less continuous ducts passing through it and the walls of these ducts offer a large heat transfer surface to the fluids passing through them. Regenerators are *reversed* at fixed, usually regular, time intervals. Both fluids thus flow *alternately through the same cross-section* of each regenerator. The passages of the fluids, between which heat is exchanged, are *separated in time* but not spatially. The heat-storing mass removes heat or "cold" from the fluid passing through it, and after the reversal, releases it to the other fluid. At least two regenerators are needed for uninterrupted operation so that continuously and simultaneously heat can be removed from one fluid in one regenerator and can be released to the second fluid in the other regenerator. Regenerators with a rotating heat storing mass are an example of this; see Fig. 11-3.

Both recuperators and regenerators can be operated in *parallel flow*, *counterflow* or even *cross flow* mode. In parallel flow both fluids flow in the same direction through the heat exchanger. In recuperators parallel flow only allows the temperatures of the two fluids to approach a common average value. On the other hand with counterflow, in which the fluids flow in opposite directions through the heat exchanger, at least one of the two fluids can reach, theoretically, the entry temperature of the other. Consequently the heat transfer performance of counterflow is superior to parallel flow. In regenerators also, it represents the most favourable mode of operation and is used almost exclusively.

Finally, *cross flow* consists of the two fluids flowing at right angles, or approximately at right angles, to one another. Until now it has only been possible to use cross flow operation in recuperators although basically there is no reason why it could not be employed in regenerators. Given large enough heating surface areas and adequate heat transfer coefficients pure cross flow is superior in operation to parallel flow but none the less is inferior to counterflow. However cross flow has the particular advantage that a higher rate of heat transfer occurs when the gas passes over the outside surface of the tubes in a direction perpendicular to, instead of parallel to, the axis of such tubes. On this basis cross flow is often combined favourably with counterflow, for example in so called "mixed switching" or in the cross-counterflow modes of operation in low temperature technology (see Sec. 8-2).

It is not unusual for the heat transfer between two fluids to be accompanied by changes in state in one or both fluids, for example, liquids evaporating or gases and steam condensing. Conventional evaporators and condensers can thus be regarded as heat exchangers, as can those heat exchangers which operate as an evaporator on one side and as a condenser on the opposite side of the partition wall through which heat is transferred. However as evaporators and condensers represent an area of specialisation frequently considered elsewhere, problems in this area will be mentioned only briefly here. Further, it must be noted that numerous individual components, in liquid or solid form, can become separated from the fluid and are deposited on the walls of the heat exchanger; this usually occurs in low temperature technology and indeed is usually an unwelcome side effect. The reverse case can be of practical importance, for example in evaporative cooling where the evaporation of a liquid to which heat is transferred in the exchanger, takes place; however this will not be considered further in this book.

As has been pointed out solid substances can also take the role of a fluid in a heat exchanger. An example is provided by the ancient process of preheating pottery before firing; this is achieved by passing the pots through an oven heated by the waste gases from the kiln which flow over the pots moving in the opposite direction. Historically processes of this type represent the first uses of counterflow. Another example is the pusher furnace which is frequently used in the iron and steel industry; here steel slabs are slowly advanced through a hot gas. A recent suggestion is to transfer the heat contained in one gas to a moving granular solid material or "fluidised bed" which in turn releases the heat to another gas in a second heat exchanger; see for example [G2, N205]. The solid particles can be guided to flow either against, or across, an existing current of gas. This usually applies to recuperators, in which one of the fluids is stationary.

1-3 BASIS OF HEAT EXCHANGER CALCULATIONS AND STRUCTURE

Research into the principles of heat transfer has provided a secure basis for heat exchanger calculations. Fundamental to these are, above all, the works of Nusselt [N4 to 11], who has applied the similarity principle to heat transfer, enabling numerous test results relating to heat transfer to be presented in a clear, practical and simple form. Other experimental results show the need to take into account the influence of thermal radiation, the effect of which can be very considerable at high temperatures.

The principles of heat transfer and the drop in pressure combine quite clearly and form the basis for experimental calculations for heat exchangers. These principles will be described in Part Two of this book. These can be dealt with relatively briefly as more precise details can be obtained from other publications [1 to 19, esp. 1, 2 and 3].

Once the heat transfer coefficient is determined, a separate calculation is still necessary in order to obtain the thermal efficiency of a given heat exchanger or to estimate the necessary dimensions for given operating conditions and to determine the optimal design. The necessary calculation procedures can be derived by purely theoretical methods. The tracing of the temperature distribution in heat exchangers forms the basis for this. In recuperators this temperature profile usually only depends on the longitudinal coordinates. On the other hand, in regenerators chronological temperature changes also play an important part. From this emerges the idea that regenerators are essentially much more complicated than recuperators. In spite of this, however, in almost all cases, simple calculation procedures are indicated.

In the Preface it was mentioned that the main task of this book is to bring together the theories which secure the foundations of the methods of calculation and which are very numerous, reflecting the many forms of heat exchanger. These will appear in Parts Three and Four.

1-4 NOMENCLATURE

Objections can be raised to the term "heat exchanger", because heat is only transferred from one material to another in one direction, and no second quantity of heat exists, moving in the opposite direction, with which this heat can be said to be exchanged. However it is quite possible to conceive from physical, and particularly kinetic considerations, of a partial exchange of energy between one heat flux and another, moving in opposite directions, as witnessed by heat transfer by radiation.

But other reasons can be suggested for using the term "exchange". One perhaps arises from the idea of an exchange of heat with "cold", but this is nevertheless physically incorrect. Another reason might be that two mediums of the same heat capacity exchange their temperatures, indeed, in ideal circumstances, each medium takes as its exit temperature, the inlet temperature of the other medium. In

Germany the most appropriate expression "Wärmeübertrager" has been proposed, which translated into English would be "heat transferer" or "heat transmitter". However this expression has not been adopted despite various recommendations that it should be used. Moreover the terms "heat exchange" and "heat exchanger" are used internationally, so that whatever misgivings there might be, these terms cannot really be avoided.

In Germany regenerators have been occasionally called "Wärmespeicher" or "Kältespeicher" which mean "heat storage unit" or "cold storage unit". However these terms can be misleading. They suggest the primary function of the regenerator is to accumulate waste or surplus heat with a view to its recovery at a later time when there is an energy shortage. While this might be the aim in certain applications, the term "regenerative heat exchanger" is probably more appropriate in most other circumstances since it rightly suggests that the storage of heat is not an end in itself, but is a means to an end.

1-5 BIBLIOGRAPHY

Foreword

Bibliographies are to be found at the end of each large section.

A list of books and papers on the general area of heat transfer follows in Sec. 1-6. The more specialized lists further on in the book are tabulated in the alphabetical order of the surnames of the authors together with a reference number. The bibliographies on the various subjects begin with the following reference numbers:

1: Heat transfer in tubes and ducts (p. 42)
41: Heat transfer in cross flow, in finned tubes and in packed beds (p. 69)
61: Heat transfer in condensation and evaporation (p. 85)
101: Radiative heat transfer (p. 111)
151: Pressure drop (p. 129)
201: Recuperators (p. 279)
301: Regenerators (p. 481)

1-6 LITERATURE IN THE GENERAL AREA OF HEAT TRANSFER

Books

1. VDI-Wärmeatlas. Düsseldorf: VDI-Verlag 1953; Supplements 1956–1963; 2nd ed. 1974.
2. Gröber, H.; Erk, S.: Die Grundgesetze der Wärmeübertragung. 1st ed. by Gröber, 1921; 3rd ed. revised by U. Grigull. Berlin, Göttingen, Heidelberg: Springer 1955; Neudruck 1961.
3. Eckert, E.: Einführung in den Wärme- und Stoffaustausch. 1st ed. 1949; 3rd ed. Berlin, Heidelberg, New York: Springer 1966.
4. Eckert, E. R. G.; Drake, R. M.: Heat and Mass Transfer. New York, Toronto, London 1959.
5. Schack, A.: Der industrielle Wärmeübergang. 7th ed. Düsseldorf: Verlag Stahleisen 1969.
6. Jakob, M.: Heat Transfer. New York: John Wiley, vol. I 1949, vol. II 1957.

7. McAdams, W. H.: Heat Transfer. 6th ed. London: Chapman & Hall, vol. I 1958; vol. II 1959 (first ed. 1933 and 1942).
8. Fishenden, M.; Saunders, O.: An Introduction to Heat Transfer. Oxford: Clarendon Press 1950.
9. Giedt, W. H.: Heat Transfer. Toronto, New York, London: Nordstrand Comp. 1958.
10. Bird, R. B.; Steward, W. E.; Leighfoot, E. N.: Transport Phenomena. New York: John Wiley 1960.
11. Petuchov, B. S.: Experimentelle Untersuchung der Wärmeübertragung. Berlin: Verlag Technik 1958.
12. Chapman, A. J.: Heat Transfer, 2nd ed. New York: The Macmillan Comp. 1967.
13. Luikov, A. V.; Mikhailov, Ju. A.: Theory of Energy and Mass Transfer. Revised English Edition. Oxford, London, Edinburgh, New York, Paris, Frankfurt: Pergamon Press 1965.
14. Ibele, W.: Modern Developments in Heat Transfer (14 Papers by various Authors). New York and London: Academic Press 1963.
15. Haase, R.: Thermodynamik der irreversiblen Prozesse. Darmstadt: D. Steinkopf 1963.
16. Kays, W. M.: Convective Heat and Mass Transfer. New York: McGraw-Hill 1966.
17. Eckert, E. R. G.; Irvine, T. (Editors): Progress in Heat and Mass Transfer. Oxford, London, Edinburgh, New York, Paris, Frankfurt: Pergamon 1971.
18. Rohsenow, W. M.; Hartnett, J. P.: Handbook of Heat Transfer. New York: McGraw-Hill 1973.
19. Dwyer, O. E. (Editor): Progress in Heat and Mass Transfer. Oxford: Pergamon 1973.

Presentation of the theory of heat transfer in extracts from books and collected works

20. Landolt-Börnstein: Zahlenwerte und Funktionen aus Physik, Chemie, Astronomie, Geophysik und Technik, 6th ed. Berlin, Göttingen, Heidelberg; in particular vol. II, 5a, 1969 (Viscosity) and vol. IV, 4: Wärmetechnik, Part a, 1967: Thermodynamic entropy (including density); Part b, 1972 Transport phenomena (Thermal conductivity) and Heat transfer.
21. Schmidt, E.: Einführung in die technische Thermodynamik. 9th ed. Berlin, Göttingen, Heidelberg: Springer 1962, pp. 347–408.
22. Nesselmann, K.: Angewandte Thermodynamik. Berlin, Göttingen, Heidelberg: Springer 1950, pp. 254–301.
23. Hofmann, E.: Wärme- und Stoffübertragung. Handbuch der Kältetechnik edited by R. Plank, vol. III. Berlin, Göttingen, Heidelberg: Springer 1959, pp. 187–463.
24. Grassmann, P.: Physikalische Grundlagen der Chemie-Ingenieur-Technik. Aarau und Frankfurt: Verlag Sauerländer 1961, Chapter 9, pp. 593–698: Impuls-, Wärme- und Stoffaustausch.
25. Hütte, Des Ingenieurs Taschenbuch, Bd. I, 28th ed. Berlin: Ernst and Sohn 1955, pp. 491-506.
26. Haselden, G. G.: Cryogenic Fundamentals. London and New York 1971, pp. 17–197; see, in particular, pp. 92–197.

PERIODICALS

Special periodicals

Heat and Mass Transfer; Journal of Heat Transfer; Int. Journal of Heat and Mass Transfer; Révue Génerale de Thermique.

Numerous other periodicals also publish essays on heat transfer. The following are only mentioned by way of example:
Brennstoff–Wärme–Kraft; Stahl und Eisen; Chemie-Ingenieur-Technik; Verfahrenstechnik, Mainz; Kältetechnik–Klimatisierung.

In addition many magazines publish regular reviews of new research papers, for example:
Eckert, E., et al.: first reported in Mechan. Engng., then in 83 (1961) 7, 34–42 and 8, 56, 57; since 1964 in Int. J. Heat Mass Transfer, e.g. 17 (1974) 615–624. Fortschritte der Verfahrenstechnik. Weinheim: Verlag Chemie, e.g. 7 (1967) 347–394, Review of the years 1964 and 1965; 8 (1969) 328–389, Review of the years 1966 and 1967.

The report of the 5th International Heat Transfer Conference in Tokyo 1974 contains comprehensive material.

PART TWO

HEAT TRANSFER AND PRESSURE DROP PARTICULARLY IN TUBES AND DUCTS