High Temperature Heat Exchangers

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HIGH TEMPERATURE HEAT EXCHANGERS

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HIGH TEMPERATURE HEAT EXCHANGERS

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This volume contains papers from the XVII Symposium of the International Center for Heat and Mass Transfer on High Temperature Heat Exchangers, held in August 1985 in Dubrovnik, Yugoslavia.

The symposium was organized to focus attention on heat and mass transfer processes associated with high temperature heat exchangers. Understanding of the processes plays an essential and important role in the rapid development of high temperature exchangers for improvement of energy utilization and efficiency of energy conversion in various power and industrial plants.

The objective of the Dubrovnik meeting was to bring together researchers and engineers to exchange information on both basic and applied research and technologies in developing high temperature heat exchangers. Contributed, invited, and general papers were organized into sessions on general basic research areas and on specific fields such as heat recovery and power and industrial plants. The same format has been followed in arranging this volume. Future possibility of new development of advanced high temperature heat exchangers using new ceramics or other high technology is seen as the future strategy of heat exchangers in this symposium.

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1. INTRODUCTION

This paper aims to give a general review of present status of high temperature heat exchangers and discuss some problems of their future development. In high temperature heat exchangers, mainly gas-gas heat transfer is carried out. Even though some regenerative high temperature heat exchangers such as those used for blast furnaces have been put to practical use, there are serious demands for the development of other kinds of high temperature heat exchangers with the object of energy saving and effective utilization. Research and development on many kinds of high temperature heat exchangers of recuperative, regenerative and direct contact types are under way and some pilot plants have been built and tested. In addition to heat transfer enhancement problems peculair to high temperatures, there are several very important and particular problems in high temperature heat exchangers such as reliability, effects of physical property variation, heat transfer deterioration due to high heat flux, construction by taking account of thermal stress and thermal expansion and difficulty in scale-up. Selection of the type and construction most adequate for a specified purpose is highly required and discussion on the items cited above will be also made in this paper.

In high temperature heat exchangers, most of the heat transfer between one gas flow and another is carried out, because even in the supercritical boiler the temperature of the generated steam and the boiler tube rarely exceeds 600°C even though the pressure is extremely high. The over-all gas-gas heat transfer is the ultimate purpose of a regenerative high temperature heat exchanger such as those used in steel industries, but it is clear that the gas flow and the solid surface play the basic role of heat transfer. In addition to this gas-solid heat transfer,direct contact heat transfer at high temperatures has been investigated and put into practice only recently for the purpose of recovering the sensible heat of hot melten slag and hot dry coke in steel industries.

It may be noted that research and development of high temperature heat exchangers was seriously initiated under various demands at the first oil shock in 1973 and that energy saving and energy effective utilization have been promoting R & D of many kinds of high temperature heat exchangers. High temperature heat exchangers can be classified into two main categories. One is the indirect contact heat exchanger and the other is the direct one.

Table 1 shows a classification of high temperature heat exchangers known at present. The indirect heat exchanger usually has the elements for the so-called pressure boundary element and the heat transfer surface. On the other hand, the direct contact heat exchanger recently put into practice in steel industries is mainly operated at almost atmospheric pressure. The stress problems at high temperatures which includes thermal stress, should be well assessed, but few standard assessment codes are well established at present at temperatures higher than about 710°C which is the highest temperature limit of fast breeder reactors. Except the stationary regenerators for air pre-heating for blast furnaces mentioned above, other high temperature heat exchangers have not been operated on a practical scale or for a length of time required for practical use. One of the most serious problems associated with this slow development speed of high temperature heat exchangers is often caused by the stress problem rather than the heat transfer one.

In order to show a standard of the usable temperature range of various high temperature heat exchangers, information and some experimental data available of it are shown in Fig.1 except for direct contact heat exchangers. The solid line shows the hot gas temperature and the broken line the heat transfer surface temperature range, respectively. The right ends of these lines

I. Indirect heat exchangers:
- 1. Recuperative type:
  - a. Metallic surface:
    - (i) Shell-tube type
    - (ii) Plate-fin compact type
  - b. Ceramic surface:
    - (i) Shell-tube type
- 2. Regenerative type:
  - a. Metallic heat storage material
  - b. Ceramic heat storage material
    - (i) Stationary type
    - (ii) Rotary type:

II. Direct contact heat exchanger:

TABLE 1 Classification of high temperature heat exchangers

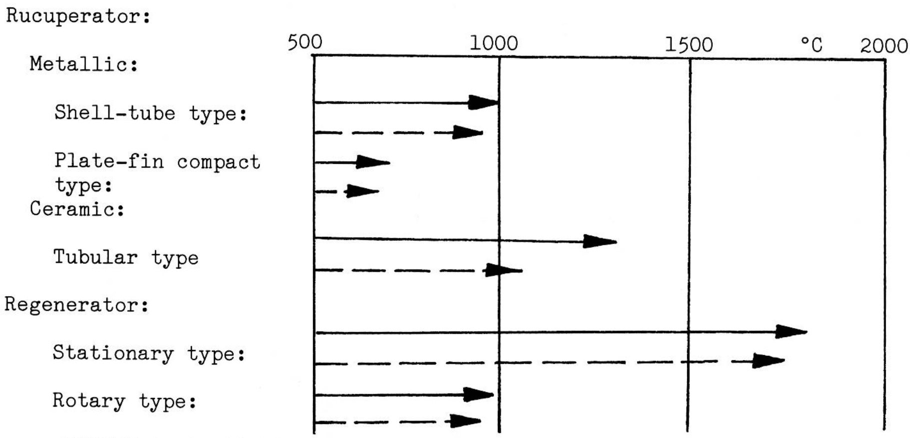

FIGURE 1 Available temperature range of various heat exchangers.

indicated by the arrow show the highest temperatures. In other words, the right end of the solid line is the inlet temperature of hot gas and that of the broken line is the highest wall temperature the element of which should be assessed by the allowable stress as discussed. As is explained in detail later on, one of the most important factors that should be considered in developing and designing a high temperature heat exchanger is its durability. The life is not only dependent on corrosion, but rather more on creep performance of construction material. Consequently, the usable temperature limit of the heat exchanger should be discussed under the condition of given durability. Since the construction material of various heat exchangers given in Fig.1 is mostly under research and development and their duration is not clear, the figure is shown to give a general idea according to data reported so far.

In discussion on high temperature heat exchangers, first of all, difference between problems about heat transfer at high temperatures and those about high temperature heat exchangers should be clearly recognized. In other words, problems of research and development of advanced or future high temperature heat exchangers should be related to the following points together with heat transfer augmentation.

(1) Heat transfer augmentation, particularly by use of radiative heat transfer.
(2) Reliability of construction and its elements taking into consideration thermal stress, creep rupture and vibration.
(3) Effects of varying physical properties including deterioration of heat transfer performance due to high heat flux.
(4) Problems related to thermal expansion of heat exchanger elements and connecting pipes.
(5) Thermal insulation of the heat exchanger itself and pipings.
(6) Various problems associated with scale-up of the capacity of exchanger.

In the following sections, while I will discuss concrete and specific problems related to several promising and representative high temperature heat exchangers, the important points given above will be explained in connection with their substances which should be seriously investigated and referred to in the research and development of a new high temperature heat exchanger. Summing up reported research and development activities and results about high temperature heat exchangers, it may be concluded that most of the advanced research and development activities have been stimulated by the targets to develop new power plants such as higher temperature gas turbine combined plant, high temperature gas cooled reactor, MHD combined power plant, fuel cell plant of the first and second generations and advanced Stirling engine. With this understanding and background, several high temperature heat exchangers worth noticing will be taken up in this paper and their problems associated with the points given above will be discussed. Among the various kinds of high temperature heat exchangers, the shell-tube metallic type is considered to be satisfactory under the most serious conditions of being used in the multi-purpose high temperature gas cooled reactor (HTGR) in consideration of performance and reliability. Because the high temperature heat exchanger or HTGR fulfils the function to supply heat not only to the conventional steam plant but to plants and processes of other purposes and has to fully satisfy the safety and reliability condition as an important constituent part of nuclear reactor.

In general, high temperature heat exchangers have to be provided with the structure of symmetry as the primary important condition. Depending on the kind of heat exchanger, the condition of symmetry is different. The shell-

tube recuperator and the regenerator for high temperature uses should be of axial symmetry, while the plate-fin compact heat exchanger for high temperature has to be of plane symmetry. This condition of symmetry should be satisfied particularly for the outer shell and elements at high temperatures including the heat transfer tubes. Therefore among the shell-tube heat exchangers, only a few types can be qualified for high temperature use. The symmetrical construction of a heat exchanger can not only mitigate the thermal stresses at its hottest place, but prevent the local high stress caused by accumulated thermal expansion of the surrounding elements. These factors result in protecting the heat exchanger constitutive material from creep-fatigue rupture.
Another important point related to the construction of high temperature heat exchangers is to fulfil the condition of a uniform outlet temperature of heated gas. To raise the outlet temperature of the heated gas at the specified value is one of the important conditions seriously required of the heat exchanger. The highest temperature of heat transfer tube should be kept as lowest as possible in consideration of the creep rupture performance of tube material. It should be noted in relation to this problem that even if heat transfer tubes are of the same length and the the hot and cold gases have a uniform temperature distribution, respectively, in the inlet conditions the outlet temperatures of the hot and heated gases are not necessarily uniform. From this fact it can be comprehended that in less carefully designed high temperature heat exchangers the heat transfer performance might be different with the individual tubes. In the case of the creep rupture performance of superalloys at temperatures of about 900°C, the rise of tube temperature in this temperature range by about 50°C does cause the reduction of creep rupture life by about 60 %. This result of investigation requires a very accurate prediction of heat transfer performance of individual tubes and of the total heat transfer performance; otherwise the part of tubes at the heated gas outlet where the temperature is higher than the average cannot hold for the length of time expected on the life calculation. Therefore the nonuniformity of the outlet temperature of heated gas should be avoided by all means and this condition has to be taken into account in the selection of the type, for example, of metallic shell-tube heat exchanger for a specified purpose.

In addition to the symmetrical construction and the uniform outlet temperature, the third important factor prerequisite for the tube arrangement is the compensation of thermal expansion and the fourth is the flow induced tube vibration. In consideration of joining the tubes to the header of the exchanger the use of straight metallic or ceramic tubes is less preferable for the high temperature heat exchanger. The compensation of thermal expansion gives predominance to the heat transfer tubes of coil and U types. The problem of flow induced vibration by vortex pouring out of the cylindrical tube is a very serious problem in gas-gas heat exchangers. Continuation of tube vibration for a long time may cause creep-fatigue rupture and an effective means to control the tube vibration induced by gas flow should be provided in the exchanger.
Judging from the reliability and safety guarantee and the several required conditions explained above, the metallic shell-tube heat exchangers of helical or U tube type are considered to be the most adequate to the HTGR application loop. More detailed discussions and information about this problem will be given in the next section as the high temperature metallic heat exchanger is one of the representative for this purpose.

The plate-fin compact heat exchanger is considered to have wide applications when it is so developed as to be available at high temperatures. It will be possibly used for high temperature gas turbine plants and advanced fuel cell plants. A detailed discussion will be made later on.

In the following, in addition to these two important metallic heat exchangers, several other promising heat exchangers will be discussed, but the direct contact heat exchanger is not treated of due to limited space.

2. METALLIC HIGH TEMPERATURE HEAT EXCHANGERS.

2.1 Shell-tube Heat Exchangers

The shell-tube metallic high temperature heat exchanger had better be discussed in relation to HTGR, because HTGR imposes most severe conditions on heat exchangers. Consequently, this paper mainly deals with problems associated with the He-He high temperature heat exchanger for shell-tube types. The reactor outlet temperature of future practical HTGR is considered to be about 950°C as the experiment made in the AVR reactor of KFA in FRG in 1975 was successfully performed at 950°C and under the condition of low total radio-activity. Since then, KFA has been making several proposals about nuclear process heat applications and testing chemical heat pipe systems.
In Japan, the research and development of nuclear steel-making technology using high temperature reducing gas produced by nuclear heat was conducted for nine years from 1973 as one of the national research and development programs by the Agency of Industrial Science and Technology, Ministry of International Trade and Industry. The Association of Nuclear Steel-making was established to implement this project. The Association organized several substantial committees and among them a committee chaired by myself was in charge of research and development of a high temperature He-He heat exchanger, its essential components and helium loops. The components and loops were manufactured and tested by Ishikawajimaharima-Heavy-Industry (IHI) Co. Ltd of Japan. In the main and hottest loop, HTGR was simulated by an electric heater. The helium flow rate in this primary loop was 1740 kg/h and that of the secondary loop was 1789 kg/h. The inlet temperature was set at 1000°C in consideration of future development of HTGR. The high temperature heat exchanger between the primary and the secondary loops was the world first heat exchanger operated at the highest temperature. A serious and troublesome research and development was carried on to design and manufacture the exchanger of superior performance that would satisfy the necesary conditions given in the preceding section. Some important information and results obtained in this project are referred to in this section.
So far many proposals about utilization of nuclear heat of HTGR from 800°C to 850°C have been made for the reactor outlet temperature of 950°C in consideration of the temperature drops in the first and second intermediate heat exchangers. Among the proposals made so far, some failed to hold the interest of people, but the recent advanced coal gasfication and new hydrogen production technologies are again drawing the attention of people in energy field to HTGR. Particularly, the advanced technology to produce hydrogen in an economical way and the enviromental superiority of hydrogen as fuel are part of the main reasons to make HTGR again the focus of attention for people in the nuclear power field. The conventional reaction of hydrogen production is the reforming reaction, but several economically competitive processes by use of water thermal-decomposition have been in progress. In order to produce hydrogen by reforming reaction or water decomposition, the heat of about 800°C is necessary.
In the development of a high temperature metallic heat exchanger, first of all, the material of tube most suitable to the working temperature and pressure specified for the purpose should be investigated and determined.