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SOLVING THERMAL/HYDRAULIC PROBLEMS IN HEAT EXCHANGERS BY FLOW-REDISTRIBUTION

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ABSTRACT

Most intermediate heat exchangers in sodium cooled fast reactors have a bundle consisting of straight tubes fixed between two tubesheets.

Due to manufacturing tolerances, an imbalanced primary massflow in the edge-channels may lead to untolerable temperature differences between the tubes in the inner and/or outer row and the mean tube temperature of the bundle.

The differences in the outer tubes of the bundle will increase even more if a primary by-pass flow occurs at the outer side of the flow shroud, which cannot be avoided when the bundle should be removable.

It will be shown that a redistribution of the secondary massflow is a usefull tool for solving these problems; use has been made of testresults of the heat exchanger of the SNR-300, a sodium cooled fast reactor, being under construction in Kalkar, West-Germany.

INTRODUCTION

A sodium cooled fast reactor consists of a primary sodium circuit, a secondary sodium circuit and a water/steam circuit. Heat produced in the reactor core is transferred from the primary circuit to the secondary circuit by means of a sodium-sodium heat exchanger, called the Intermediate Heat Exchanger (IHX).

The secondary sodium circuit and the water/steam circuit are coupled by means of a sodium heated steam generator.

The IHX has a safety function. When a severe sodium- water reaction would occur in the steam generator, it has to withstand the pressure waves, caused by the reaction, in order to protect the reactor core.

There are two types of primary circuits in fast reactors. The first type consists of a large vessel, containing the reactor core, the recirculation pump and the IHX (pool-type reactor). The other type consists of a vessel, containing the reactor core and a piping system outside the reactor vessel in which the pump and the IHX are located (loop-type reactor).

DESCRIPTION OF THE INTERMEDIATE HEAT EXCHANGER

In a pool-type as well as in a loop-type primary system the IHX is being fed with secondary sodium entering at the top of the component and flowing downwards through a central downcomer. At the lower end of the component the sodium enters a distribution chamber ("floating" head) and flows upwards through the tubes, that have been fixed between two tube sheets.

The secondary sodium is being collected above the upper tube sheet in an annular chamber, surrounding the central downcomer and leaves the component via a lateral outlet-nozzle.

The bundle is composed of two tube sheets being interconnected by a central tube and the straight heat transfer tubes. In order to avoid thermal interaction between the secondary sodium flowing through the central downcomer and the primary sodium in the bundle, flowing along the centrale tube, the gap between the two walls is gasfilled.

The outer tube row of the bundle is surrounded by a flowshroud. In the IHX of a loop-type reactor the primary sodium flows through a primary inlet nozzle into an inlet annulus and is distributed along the circumference. The sodium then enters the bundle part of the component, flows downwards along the tubes and leaves the IHX via an outlet annulus through the primary outlet nozzle. The IHX of a pool-type reactor needs no primary inlet and outlet annulus, since the component is directly immersed in the primary sodium of the reactor vessel.

THERMAL/HYDRAULICS

The tube bundle is enclosed at the inner side by the central tube and at the outer side by the flowshroud. The primary flow through the edge-channels of the bundle depends on the distance between the concerning tubes and the central tube respectively the flowshroud and depends also on the flow-resistance in the concerning channels. Because the geometry and the constructive elements in the edge-channels differ from the situation in the main part of the bundle, it is necessary to make a distinction between the flow and temperature distribution in the main part of the bundle and in the edge-channels.

Main part of the bundle
The described type of heat exchanger is a countercurrent one with the exception of the primary inlet and outlet regions (see fig. 1). In these regions a cross-flow situation exists. The temperature of the primary sodium in the inlet region decreases in radial direction, because of heat transfer to the secondary sodium, flowing upwards through the tubes.

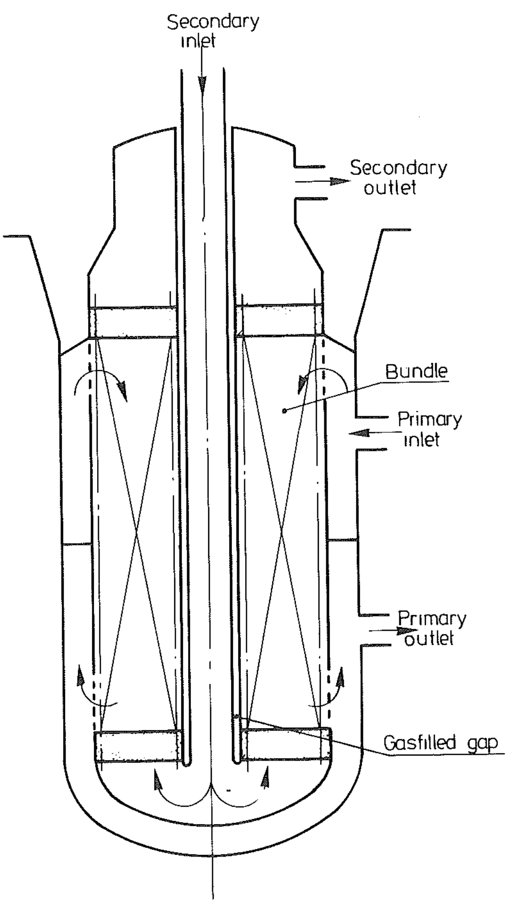

FIG. 1 SIMPLIFIED OUTLINE OF A STRAIGHT TUBE BUNDLE INTERMEDIATE HEAT EXCHANGER

If a uniform distribution of the secondary flow amongst all tubes is supposed, then the non-uniform temperature distribution of the primary sodium in the inlet region results in a different temperature increase of the secondary sodium along the tubes, depending on the radial position. So the temperature profiles of the primary and secondary sodium at different levels in the bundle are not uniform.

The temperature distribution of the secondary sodium leaving the upper tubesheet is also not uniform, but decreases from the outside to the inside.

The occurrence of non-uniform temperature profiles is being aggravated by the fact that the average axial primary massflow per tube decreases from the outside to the inside caused by the flow resistance in the primary inlet and outlet region. These phenomena becomes more evident when the ratio of bundlelength to bundlediameter decreases.

The different axial temperature profiles of the primary and secondary sodium along the tubes, depending on the radial position, cause different mean axial temperatures of the tubes. It will be clear that these temperature differences must be kept as small as possible, in order to satisfy stress criteria.

Edge-channels
The geometrical and constructive situation at the inner and outer side of the bundle differs from the situation in the main part of the bundle, caused by two factors. First the regular tubepattern, based on circular pitch or triangular pitch does not exist at the boundaries of the bundle and secondly the tubegrid-edges may cause a higher flowresistance compared to the grid-resistance in the main part of the bundle. The thermal/hydraulic aspects at the inner and outer side of the bundle will be discussed below.

Inner side of the bundle. The inner tube row is positioned at a certain distance from the central tube. This distance is amongst others being determined by the fabrication tolerances of the central tube and by the space needed for the tubegrid-edge. If the gap between the central tube and the inner tube row is too large, which means that the primary mass flow per tube of the inner row is higher than the primary mass flow per tube in the main part of the bundle, than this may lead to the following consequences. The temperature increase of the secondary sodium in the inner tubes will be higher than in the main part of the bundle. This may cause an unacceptable high mean axial temperature of the inner tubes with respect to the mean average value of the bundle.

The temperature of the central tube is being determined by the temperature of the primary sodium flowing along this tube, because calculations and experiments have shown that heat transfer through the gas-filled gap between central tube and secondary downcomer can be neglected. This means that the mean axial temperature of the central tube is higher than the mean axial temperature of the inner tubes, because the latter is composed from primary and secondary temperatures. So the temperature of the central tube may become to high with respect to the mean temperature of the bundle.

When the temperature increase of the secondary sodium in the inner tubes is higher than in the main part of the bundle, than the secondary outlet temperature of the concerning tubes above the upper tubesheet is also higher. This might lead, depending on the outlet temperature of the tubes at the outer side of the bundle, to unacceptable temperature differences between the inner and outer shell of the secondary outlet annulus. Besides local high temperatures in the tubesheet may be unacceptable.

If the gap between the central tube and the inner tube row is too small or if the flow-resistance caused by gridobstacles or other constructive elements is too high, in the sense that the primary massflow per tube is relatively too small, than the opposite phenomena, as mentioned before, will occur.

Outer side of the bundle. The outer tuberow of the bundle is surrounded by a flowshroud. The gap between the outer tubes and the flowshroud must be kept within certain limits in order to prevent that the mean axial temperature of the concerning tubes becomes too high or too low with respect to the mean bundle-temperature. The secondary outlet-temperature of the outer tubes also must not deviate to much from the other tube outlet temperatures, especially not from the outlet-temperature of the inner tubes, in order to avoid stress problems in the secondary outlet annulus and/or in the upper tubesheet.

The flowshroud is fixed at the grid-edges or is fixed at the upper or lower tubesheet. This means that the flowshroud has the capability of free thermal expansion, in contrast with a rigid central tube, being fixed between the tubesheets.

When in a loop-type reactor the bundle of the intermediate heat exchanger must be removable, it is unavoidable that a primary bypass-flow occurs between the removable part and the non-removable part of the IHX. This bypass will occur at the outer side of the flowshroud. The primary sodium flow will transfer heat to the outer channel of the bundle which results in an (additional) temperature increase of the outer tubes and of the secondary sodium at the outlet of these tubes.

DESIGN TOOLS FOR TACKLING THE THERMAL/ HYDRAULIC PROBLEMS

In the previous chapters a general description of the intermediate heat exchanger has been given and thermal/ hydraulic aspects of the bundle were discussed. There are possibilities to eliminate or to reduce the problems caused by an imbalanced primary flow in the edge-channels, caused by the temperature decrease of the primary sodium in the inlet region of the bundle and/or caused by by-pass flows outside the flow shroud.

An obvious way of reducing these problems is to balance primary flow in the edge-channels by adopting tight tolerances, to minimize entrance- and exit effects by using a slender tube bundle and to eliminate by-pass flows by using an effective seal. When considering system requirements, manufacturing conditions, cost etc., non of these remedies appears to be very attractive. Therefore, other solutions should also be considered:

- expansion bellows in the central tube
- expansion bends in the bundle tubes
- flowbaffles on the primary side
- flowredistribution devices on the secondary side.

Expansion bellows in the central tube

Generally there will be a difference between the mean bundle temperature and the mean temperature of the central tube. This difference must be kept limited in order to avoid unacceptable thermal stresses. If an expansion bellows would be placed in the central tube, a too large primary flow in the inner channel would not further affect the central tube. A too high temperature of the inner tubes and a too high secondary outlet-temperature remain nevertheless possible.

The thermal response of the central tube on the one side and the bundle tubes on the other side is not the same during transient conditions, caused by the different wallthicknesses of the central tube and the bundle tubes. Besides, transients entering from the secondary sodium circuit, sooner affect the bundle tubes than the central tube. This might temporarely lead to unacceptable temperature differences. An expansion bellows in the central tube eliminates the consequences of too large temperature differences during transients and steady-state operation. A bellows is ineffective to compensate for an unbalance in primary flow.

Expansion bends in the bundle tubes

Another possibility to eliminate the interaction between the central tube and the bundle tubes is the introduction of an expansion bend in all bundle tubes as has been applied in the IHX of the FFTF [2]. The advantage of these bends compared with the expansion bellow in the central tube is that every bundle tube can expand. This implies that an imbalanced primary flow at the inner or outer side of the bundle neither affects the central tube nor the tubes in the inner and/or outer row.

Temperature differences at the secondary outlet must nevertheless be kept limited, in a different way, for earlier mentioned reasons.

Flow baffles on the primary side

The occurance of temperature differences in the main part of the bundle, caused by the lateral inletflow of the primary sodium, can be strongly reduced by applying flow baffles on the primary side of the bundle as has been applied in the IHX of the CRBR [2]. The baffles are alternately fixed at the flow-shroud and the central tube. They create a high flow resistance in axial direction on a main part of the cross-section of the bundle;

this introduces a cross flow pattern for the primary sodium along the total bundle. If the inner and/or outer channels of the bundle are too large, then the flow baffles will not prevent that the tube-temperatures of these rows become too high.

In primary systems of fast reactors, in which the IHX is located at the suction side of the circulationpump, only a very limited pressure loss is acceptable. In that case primary flow baffles are difficult to apply.

Flow redistribution devices on the secondary side

In the secondary distribution chamber ("floating" head) of the IHX the sodium is distributed among the tubes. In the ideal situation that no imbalanced primary flow occurs in the inner and/or outer channels, that the cross flow influence in the primary inlet region can be neglected and that no by-pass flow occurs around the flowshroud, an equal distribution among all bundle tubes should be realised.

Because of fabrication tolerances of the central tube and the flowshroud imbalanced flows in the edge-channels can hardly be prevented. Besides, in a loop-type IHX, the occurance of a bypass-flow is inevitable when the bundle should be removable. It is however possible to adjust the secondary flow through those tubes, which are being affected by the above mentioned aspects. This secondary flow redistribution can in practice be realised by using a perforated plate.

When comparing advantages and disadvantages of the above four design aspects, it appears that the flow-redistribution plate, possibly in combination with an expansion bellows is attractive as a solution:

- to compensate for imbalance in primary flow
- to allow larger gaps and, therefore, larger tolerances between inner tube row and central tube and outer tube row and flow shroud.
- to compensate for by-pass flows outside the flowshroud.

For different reasons expansion bends in individual tubes and flow baffles on the primary side are considered to be less attractive.

TEST RESULT [1]

In order to reduce temperature differences caused by imbalanced flows at the outer side of the bundle of the IHX of the SNR-300, a loop-type fast reactor, being under construction in Kalkar, West-Germany, secondary flow redistribution has been applied. A prototype of the IHX has been tested; the main test results will be given in order to illustrate the feasibility of secondary flow redistribution for reducing or eliminating undesired radial temperature differences in a heat exchanger bundle.

The tubes of the bundle of the SNR-300 IHX are arranged in a triangular pitch. The central tube is cylindrical, so the inner channel has an irregular cross area in circomferenciel direction.

The flow-shroud around the outer tubes is not circular, but consists of thin stainless steel plates, which are flat at the sides where the tubes in the outer row are in line and which are corrugated at the sides where the tubes are staggered.

A main design requirement for the IHX of the SNR-300 has been, that the bundle could be removed without cutting primary piping. Removal of the bundle might be necessary for repair, replacement or in-service inspection purposes.

In order to meet this requirement, the bundle plus flow-shroud can move freely through an inner shell, which is the inner boundary of the primary inlet and outlet annulus. In order to suppress bypass-flows, a labyrinth ring has been provided at the periphery of each tube support grid in the space between flow-shroud and inner shell.

An evaluation showed that the primary flow through the outer channel as well as the by-pass flow through the gap between flow-shroud and inner shell were unbalanced when using tolerances that appeared reasonable from a manufacturing viewpoint.

Figure 2 shows the temperature distribution in the bundle when applying a uniform secondary flow distribution and applying the actual outer channel and bypass flows. This temperature distribution has been calculated with a code, that was validated with partial-load test-data.

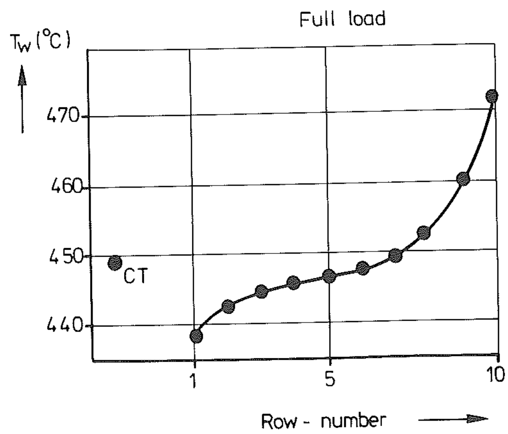

FIG. 2 MEAN WALL TEMPERATURE (T_W) OF CENTRAL TUBE (CT) AND BUNDLE ROWS. UNIFORM DISTRIBUTION OF SECONDARY FLOW.

The effect of imbalanced outer channel and bypass flows on the temperature differences in the bundle is presented in the figures 3 and 4. It concerns calculated data using the above mentioned validated code. The point A and B in these figures represent the actual situation in the heat exchanger.

It was decided to compensate the imbalanced primary flow by increasing the secondary flow through the outer tubes. This was achieved by mounting a perforated plate against the lower tubesheet. The diameter of the perforation for the outer tubes is larger than for all other tubes. This creates a lower flowresistance and thus a higher flow. An increased secondary flow through the outer tubes results in a lower mean axial temperature of the tubes and results also in a lower secondary outlet temperature.

Figure 5 shows an almost uniform temperature distribution in the bundle applying this secondary flow redistribution. From the testdata in figure 6 it can be seen that the increased secondary flow in the outer row causes a primary temperature decrease along the tubes being practically the same as in the middle of the bundle.

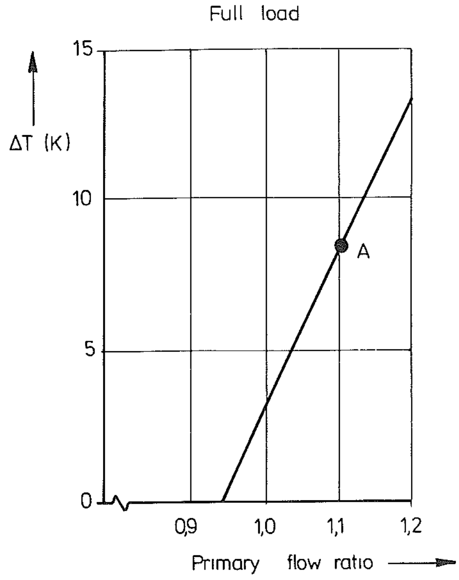

FIG. 3 INFLUENCE OF PRIMARY FLOW IN OUTER CHANNEL ON TEMPERATURE DIFFERENCES. PRIMARY FLOW RATIO = FLOW PER TUBE IN OUTER CHANNEL COMPARED WITH MEAN BUNDLE FLOW PER TUBE. ΔT = TEMPERATURE DIFFERENCE BETWEEN OUTER TUBES AND BUNDLE.

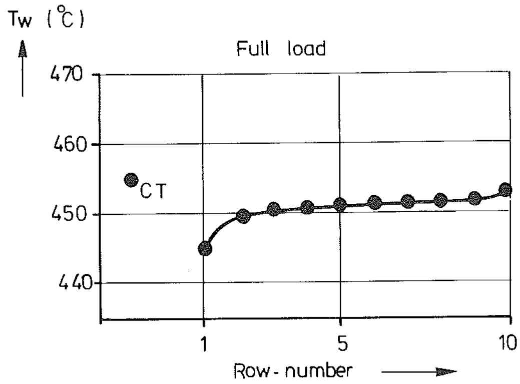

FIG. 5 MEAN WALL TEMPERATURE (T_w) OF CENTRAL TUBE (CT) AND BUNDLE ROWS. SECONDARY FLOW REDISTRIBUTION.

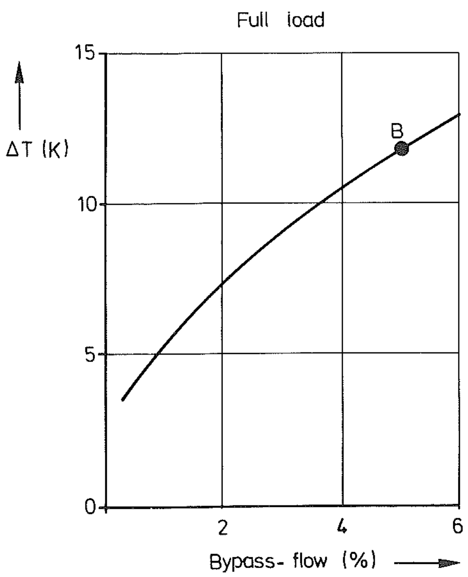

FIG. 4 INFLUENCE OF PRIMARY BY-PASS FLOW ON TEMPERATURE DIFFERENCES. ΔT = TEMPERATURE DIFFERENCE BETWEEN OUTER TUBES AND BUNDLE.

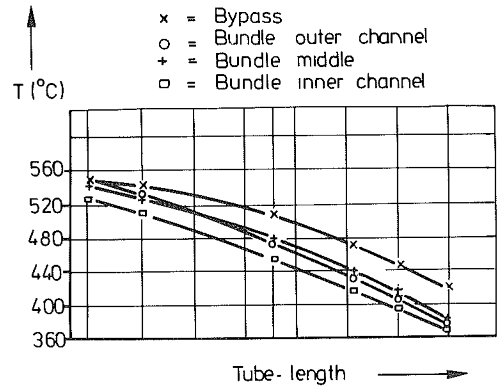

FIG. 6 AXIAL TEMPERATURE PROFILES OF PRIMARY SODIUM AT FULL-LOAD CONDITIONS

CONCLUSIONS

1. When using reasonable fabrication tolerances it is difficult to avoid imbalanced primary flows in the edge-channels of straight tube bundle heat exchangers.

2. Without complicated sealing arrangements a bypass-flow cannot be avoided when the bundle should be removable. Additional heat input from this flow into the bundle requires measures to prevent that the temperature of the outer tubes grows too high.

3. Changing the secondary flow through the tubes, that are affected by fabrication tolerances and/or bypass-flows, offers an attractive solution to avoid thermal/ hydraulic problems.

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