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Research on thermal insulation for hot gas ducts

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Abstract

The inner surfaces of prestressed reactor vessels and hot gas ducts of Gas Cooled High Temperature Reactors need internal thermal insulation to protect the pressure bearing walls from high temperatures. The design parameters of the insulation depend on the reactor type. In a PNP-plant temperature and pressure of the cooling medium helium are proposed to be 950 °C and 40 bars, respectively.

The experimental work was started at KFA in 1971 for the HHT-project using three test facilities. At first metallic foil insulation and stuffed fibre insulating systems, the hot gas ducting shrouds of which were made of metal, have been tested. Because of the elevated helium temperature in case of PNP and the resulting lower strength of the metallic parts the interest was directed to rigid ceramic materials for the spacers and the inner shrouds. This led to modified structures designed by the INTERATOM company. Tests were performed at KFA.

The main object of the investigations was to study the influence of temperature, pressure and axial pressure gradients on the thermal efficiency of the structures. Moreover, the temperatures within the insulation, at the pressure tube, and at the elements which bear the inner shrouds were measured. Thermal fluxes and effective thermal conductivities in axial and circumferential direction of the pressure tube are given, mainly for the INTERATOM-design with sperical spacers.

1. Introduction

In a PNP-plant (Prototype Nuclear Process heat project) the heat generated in the core is transferred either to the steam reformer for producing hydrogen and methanol (HVK) or to the intermediate heat exchanger and steam gasifier for producing methanol (WKV) through primary and secondary hot gas ducts, respectively. Because of the helium temperature of 950 °C and the pressure of 40 bars these ducts need an inner thermal protection system.

Since the insulating systems are filled with pressurized helium and are in contact with the hot coolant, they have to meet severe requirements. Materials used must endure all operating conditions over their lifetime. The components must be able to withstand high pressure transients, when sudden depressurization will take place.

This causes a high pressure difference between the insulation and the inner cross section. A high pressure within the insulation and axial pressure gradients may produce natural or even forced convection. Convection, however, must be kept at a low level otherwise the effectiveness of the insulation will be decreased.

In the following at first the test facilities and the insulating systems tested will be described. After that investigations on a design of INTERATOM and experimental results are discussed. Finally, some results of fibre insulations tested previously will be presented for comparison.

2. Test facilities and insulations tested

Experimental work was started at KFA in 1971 using the ARGAS-loop described by Bruners et al. /1/ and the high pressure wind tunnel (HD-channel), see Grosse and Scholz /2/. An advantage of the HD-channel is the high volume flow of about 7 m^3/s thus being four times higher than the one of the ARGAS-loop. The maximum temperature of the HD-channel is 400 °C compared to 1000 °C of the ARGAS-test facility. The corresponding pressures are 40 bars and 10 bars, respectively. In the high temperature helium test rig (HHV) which was erected for testing HHT (direct cycle High Temperature Reactor) components, the maximum temperature is 850 °C at a pressure of 51 bars. The mass flow is approximately 200 kg/s. Further details are given by Noack and Weiskopf /3/.

The test objects were mounted horizontally in the test facilities described above. Experiments in vertical position of the insulations were also carried out with stagnant gas. By means of electrical heaters hot face temperatures of 760 °C were reached.

The insulating systems which were tested up to now are listed in table 1.

1) Metallic foil insulations
- a) Bobbin design (ARGAS-loop)
- b) Element design (HD-channel and vert.)
- c) Element design (HHV-loop)

2) Stuffed fibre insulations
- a) One interm. tube (ARGAS-loop, $\rho = 280$ kg/m^3)
- b) One interm. tube (HD-channel, $\rho = 400$ kg/m^3)
- c) Two interm. tubes (HD-channel, $\rho = 280$ kg/m^3)
- d) One interm. tube (HHV-loop, $\rho = 290$ kg/m^3)
- e) One interm. tube (bend) (HD-channel, $\bar{\rho} = 217$ kg/m^3)

3) Ceramic insulation
- a) Carbon rings (HD-channel and vert.)

4) Fibre blanket insulations
- a) Cover plate design (HD-channel, $\rho = 178$ kg/m^3)
- b) KWU/IA design (CFC spacers) (HD-channel, $\rho = 130$ kg/m^3)
- c) GHT/IA design (Ceramic spacers) (HD-channel, $\rho = 160$ kg/m^3)

TABLE 1.
Insulating systems

One can roughly discern between metallic, fibrous and rigid ceramic structures, /4/. The table contains also the test facilities used and the densities of the fibre insulations. It is also mentioned, when experiments were carried out with the specimen in vertical arrangement.

The metallic insulation of bobbin type was delivered by Darchem/UK for experiments in the ARGAS-loop. A special foil element insulation was also designed by Darchem for HHT applications for high axial pressure gradients and depressurization rates. The foil elements were held together by means of studs and cover plates. End sections bear the inner gas ducting shrouds. First measurements showed an excessive influence of gas pressure on the distribution of thermal fluxes and temperatures around the pressure tube. This was caused by natural convection within circumferential gaps. By closing these gaps the thermal efficiency was improved. As a consequence a similar foil insulation was manufactured for a section of the HHV tubing system.

Stuffed fibrous insulating systems designed by BBC/Switzerland for straight tubes were tested as well in the ARGAS-loop as in the HD-channel. The main components are metallic ducting shrouds, v-shaped end pieces and perforated and intermediate tubes. The annuli were filled with Kaowool the densities of which are between 280 kg/m^3 and 400 kg/m^3. The insulation for the HHV-loop was of the same design. The average fibre density of the test section was 290 kg/m^3. Densities of only 230 kg/m^3, 214 kg/m^3 and 208 kg/m^3 were reached for the segments of an insulated bend, which was also delivered by BBC. The design is similar to the insulation for straight tubes.

To study the effects of gaps and fabrication tolerances on the thermal performance an insulation made of five carbon rings was tested in the HD-channel. It was supplied by the Sigri company in Meitingen. First experiments showed that the existing gaps were too large. As a measure of improvement the rings were sealed to suppress bypass-flow due to axial pressure gradient.

A fibre blanket insulation with metallic cover plates was manufactured by BBC. The density of 178 kg/m^3 was achieved by compressing the Kaowool blankets by means of the cover plates and studs. The additional blanket insulations were constructed by INTERATOM. Contrary to the BBC design they did not contain metallic parts. The inner shrouds made of graphite were held by massive carbon fibre composite (CFC) and ceramic spacers, respectively. The blankets were wound around the inner graphite tubes.

3. Description of insulation with spherical spacers

Fig. 1 shows the scheme of a section of the INTERATOM insulation. The insulation consisted of inner shrouds made of graphite on which the fibre blankets were wrapped. At the hot side Saffil fibres of approximately 95% Al_2O_3, at the outer side Cerablanket fibres of 55% Al_2O_3 and 45% SiO_2 were used. The outer and inner diameters of the inner shrouds were 780 mm and 630 mm, respectively. The Saffil blankets were compressed by means of wire mesh and

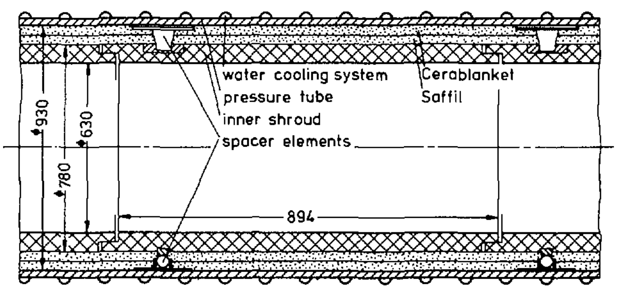

FIG. 1.
Scheme of INTERATOM insulation

the blankets at the outside by means of a sheet of metal. The mean fibre density was approximately 160 kg/m^3. Ceramic balls consisting of high density Al_2O_3 or Si_3N_4 were located at one end of the shrouds for supporting and earthquake damping of the tubes. Additionally, Al_2O_3 or Si_3N_4 elements are used for fixing the liner in axial direction.

The whole assembly and further details are given in Fig. 2. The insulation

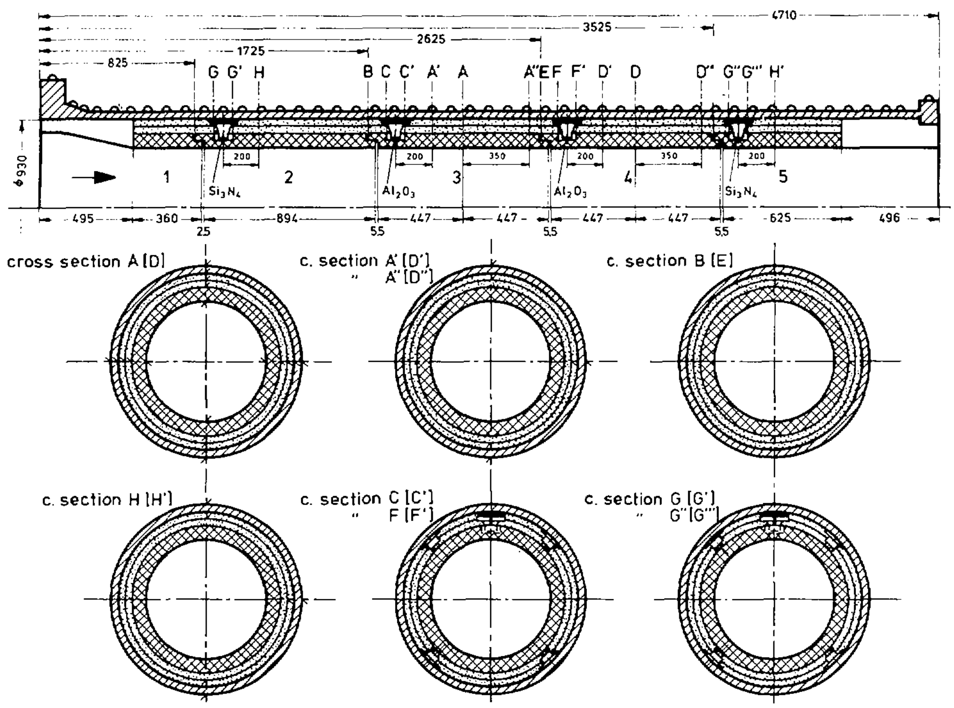

FIG. 2 Pressure tube, insulation and instrumention

consisted of 5 sections, the first and fifth of which were used as entrance and exit passages. Sections 2, 3 and 4 were test pieces. The gaps between the particular shrouds were for thermal expansion. The length of the pressure tube is 4710 mm. The inner diameter of 930 mm was equivalent to that of tubes already used earlier. Half tubes are welded to the outside for heat removal. The eight measuring systems enable to measure thermal fluxes of the sectors top, bottom, right, and left for the middle part of the insulation. In the flange region there are auxiliary systems for cooling the non insulated section of the pressure tube. Thermocouples were installed into the cooling systems and along the outer wall. The positions of the thermocouples within the insulation, at spacers and shrouds can be seen from the six cross sections. In particular, the cross sections A-A and D-D in the middle of the parts 3 and 4 were instrumentated.

The experiments were carried out in the HD-channel of KFA with air and helium as cooling media at pressures up to 40 bars. Because of the graphite corrosion the maximum temperature of the air experiments were restricted to 300 °C. Using helium the highest temperature was 400 °C. The axial pressure gradient was also varied. In total four test runs were conducted. During the first run the maximum velocity was approximately 20 m/s. In order to get higher velocities a displacement body was mounted which enabled a maximum velocity of about 39 m/s. Since the thermal fluxes of these test runs depended on pressure and pressure gradient another run was conducted with a closed metallic inner shroud which should eliminate the influence of axial pressure gradients. The results of this run, however, were not satisfactory, too. Therefore the insulation was dismantled and rebuilt after having coiled additional Sigraflex foils together with the fibre blankets as convection barriers made of graphite. Because of the lack of time only one test run with the displacement body could be carried out. During the last series the outer cooling was switched off.

Fig. 3 shows the temperatures of the pressure tube of parts 2, 3 and 4 for

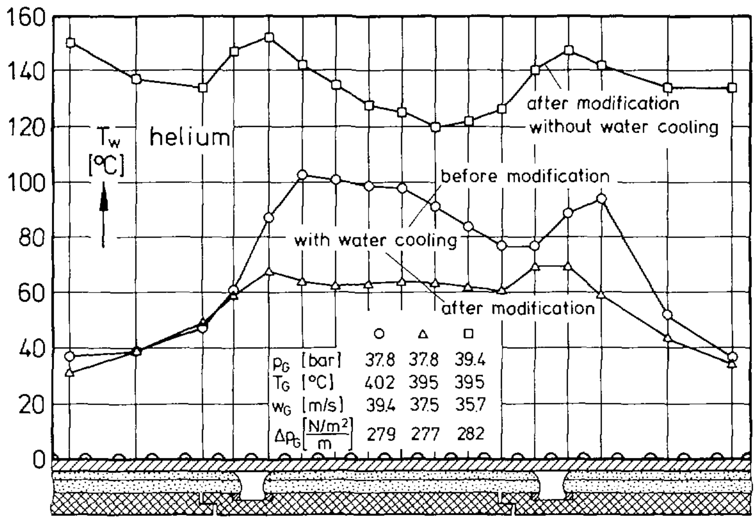

FIG. 3
Temperatures of the pressure tube

the top position and three test runs. The data for pressure, temperature, mean velocity and pressure difference of the coolant are given. The lower curves which stand for the experiments with outer water cooling can be compared. The slope of the temperatures in the region of the second and fourth section is caused by the increase of temperature of cooling water. The temperatures of the third section are approximately constant except the downstream region for the experiments before the modification, where the average temperature is 90 °C. The influence of the higher thermal conductivity of the spacer elements is demonstrated. The additional foils increase the pressure drop in radial direction, thus decreasing wall temperatures to

65 °C. Only in the region of the axial spacer the temperature is 70 °C. When the water cooling is switched off the temperature of the outer wall increases to 120 °C and 150 °C, respectively. The heat passing the insulation is transferred to the outside by natural convection and thermal radiation. Since the thickness of the fibre blankets was only 75 mm the increase of temperature by a factor of 2 seems to be high.

In Fig. 4 the total thermal fluxes in dependence upon pressure are given for helium, part I, which includes the whole section 2 and half of section 3, and for the first test run. The dependence upon pressure is almost linear.

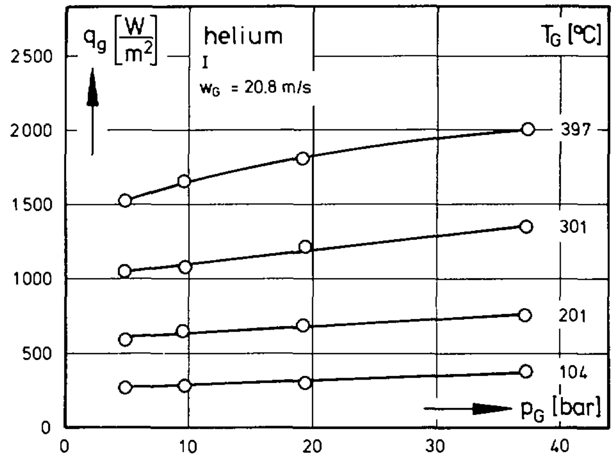

FIG. 4.
Thermal fluxes versus helium pressure

The maximum flux of 2000 W/m^2 was measured at the gas temperature of 397 °C and the pressure of 38 bars. It is lower by 55% than in case of the insulation with CFC spacer elements previously tested, /5/. The improvement is caused by the reduction of the thermal conductivity of the spacer material.

In Fig. 5 the total thermal fluxes of the experiments before and after the modification are compared. The results are given in dependence upon pressure

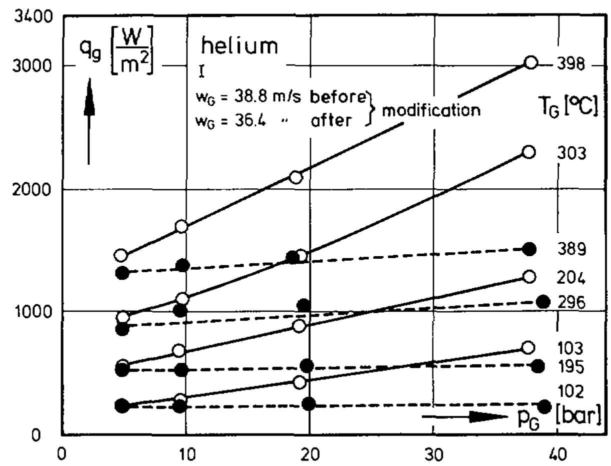

FIG. 5.
Thermal fluxes versus helium pressure

for helium, part I and the experiments with displacement body. In comparison with the results previously discussed it is striking that with growing velocity from 20.8 m/s to 38.8 m/s thermal fluxes increase by 50% at the highest pressure. This is valid for all temperature steps. In the lower pressure region, however, thermal fluxes are nearly identical in spite of different velocities. After having modified the insulation the dependence of the thermal fluxes upon pressure is only weak, as demonstrated by the dashed lines. Thermal fluxes are remerkably reduced compared to the results which stand for the unmodified insulation. At the highest pressure and temperature thermal flux was only 1500 W/m^2 and thus two times lower. This reduction is also valid for the other temperature levels. Due to the reduction of the permeability in radial direction consequently the thermal fluxes were also reduced.

The efficiency of the convection barriers with regard to the distribution around the circumference is demonstrated in Fig. 6, where Nusselt numbers

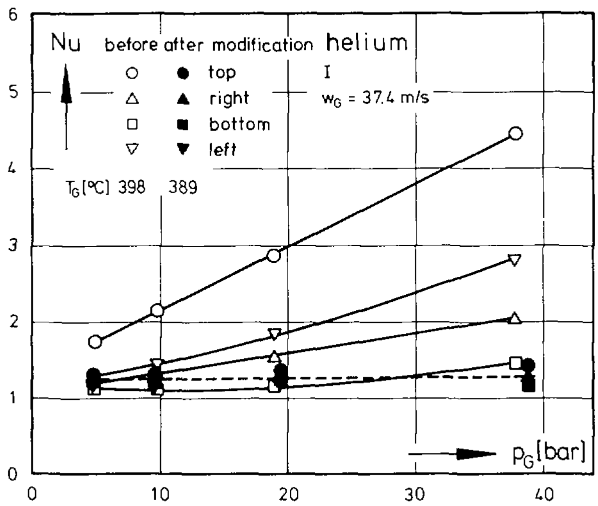

FIG. 6.
Nu number versus helium pressure

for helium versus pressure are given. The Nusselt number Nu is defined as the ratio of the effective thermal conductivity of each sector to the conductivity within the insulation, e.g. when gas movement is suppressed. The results hold for part I, the maximum gas temperature and the average velocity of 37.4 m/s. Before the modification of the structure the differences between top and bottom sectors increase strongly with growing pressure. Whereas the Nusselt number of the bottom only increases weakly from 1.1 to 1.45, in the top position it increases from 1.7 to 4.4. As shown by the dashed line the additional foils cause in particular an obvious uniformity in addition to a reduction of Nusselt number of all sectors. The highest and lowest values at the highest pressure are 1.38 and 1.15, respectively.

This improvement may be compared with the investigations on the metallic foil insulation, /6/. With growing gas temperature the differences between top and bottom sector are lowered. Since the influence of axial pressure gradients on the Nusselt number is only weak, the thermal behaviour of the insulation can be described to be good.

Similar results were gained for the stuffed fibre insulation. The experiments were carried out in the HD-channel, the ARGAS-loop and HHV-test facility /4/. The design is described in chapter 2. It is the basis for the concept developed by INTERATOM for the KVK-test facility. The Nusselt numbers in dependence upon the average temperature are given in Fig. 7 for various fibre densities and pressures. As described by Bruners et al. /1/ the influence of gas pressure is only weak. The dashed curve fits the experimental results rather well. Contrary to the metallic foil insulation

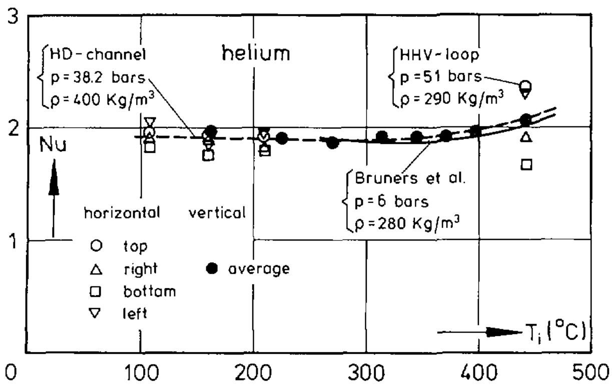

FIG. 7
Nu number versus helium pressure (fibre insulations)

tested in HD-channel the insulation whose density was 400 kg/m^3 exhibits only Nusselt numbers of 1.95 and 1.8 for top and bottom sectors, also in horizontal position. Because of the small influence of gas pressure the mean value of 2.07 of the HHV-experiments agrees with the other results, though the differences between the four sectors are higher than expected. This may be caused by irregularities of fibre densities, mainly in the region of the v-shaped end pieces. The reason for the higher values compared with those of Fig. 6 is that the effective thermal conductivity of the stuffed insulating systems is related to the total thickness. Basing on the thicknesses of the graphite tubes and blankets the Nusselt numbers of the fibre blanket insulation would be increased by a factor of 2.2. In case of the stuffed insulation the Nusselt number reaches a minimum of 1.85 at the temperature of 320 ^{o}C. Then it increases continuously. In the low temperature region the influence of free convection is stronger than that of thermal radiation, which is dominating at elevated temperatures.

4. Conclusions

A thermal insulation for the primary circuit of a nuclear power station was tested at KFA. The insulation has been developed by INTERATOM. At first the design, the instrumentation and the various test runs were described. After that the experimental results were discussed for helium as coolant. In particular the constructive improvements were mentioned. Natural and forced convection were almost suppressed by means of Sigraflex foils. Consequently, the amount of thermal fluxes and effective thermal conductivities of the four sectors was almost equal. Finally, the results of the stuffed fibre insulation previously tested were discussed, the thermal behaviour of which was quite similar.

5. References

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