Experimental Investigation on Powder Conductivity for the Application to Double Wall Bayonet Tube Bundle Steam Generator

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ABSTRACT

The 300Mth Advanced Lead cooled Fast Reactor European Demonstrator (ALFRED) adopts the super-heated steam double wall once through bayonet type bundle as SG. The single unit is constituted by three concentric tubes and is based on the concept to provide a double physical separation between the coolant (water) and the hot fluid (lead) in order to increase the safety margin of the plant by reducing the probability of liquid metal-water interaction in case of tube failure. Furthermore, this configuration allows the possibility to monitor eventual leakages from the coolant or from the hot fluid by pressurizing the annular region between the double walls. On the other hand, since its goal is to achieve high thermal performance, the annular space that separates the fluids should be filled with a porous heat transfer enhancer.

In order to fulfil the R&D need related to selection of the porous heat transfer enhancer, the Tubes for Powders (TxP) facility has been designed and constructed at ENEA. The facility consists of three concentric tubes and it allows to estimate the conductivity of a porous material by measuring the temperature drop across its borders and the removed power. It has the capability to introduce helium and to pressurize it up to 5 bar. The TxP facility has been operated for about one year with the purpose to assess the conductivity of powders both in air environment and in pressurized helium atmosphere.

The present paper focuses on the experimental campaigns carried in TxP to characterize Si-C and AISI-316 powders in support to the design of the Heavy liquid metal pressurized water cooled tubes (HERO) test section which consists of a bundle of 7 tubes representative of the ALFRED SG (tubes in full scale). The main aims of the experiments are to assess the conductivity of powders both in air environment and in pressurized helium atmosphere.
1 INTRODUCTION

There are two primary reasons for the adoption of double wall tubes heat exchangers. The first is to provide a given temperature drop between the hot fluid and the coolant (and is widely used). The second (which is the case under discussion), is to increase the safety margin by reducing the probability of interaction coolant-hot fluid. Furthermore, this configuration allows the possibility to monitor eventual leakages from the coolant or from the hot fluid by pressurizing the separation region. On the other hand, if it is required to monitor the leakages and get high thermal performance of the unit, the annular space that separates the fluids should be filled with a porous heat transfer enhancer.

The Lead cooled European Advanced Demonstrator Reactor (LEADER) project [1] has recently renewed the focus on this concept. In the framework of this programme, the superheated steam double wall (with leakages monitoring) once through bayonet type Steam Generator (SG) has been proposed [2]. Each SG includes about 500 bayonet tubes, operates at 180 bar (water side) and should generate superheated steam at 450 °C. Therefore, R&D is necessary to check and improve its TH performance [3]. In particular, due to the introduction of a double wall tube with annular gap, the thermal performance of the SG could be impaired. An important goal, is therefore to determine a candidate material as a gap filler.

In order to cope the related R&D needs, a specific facility for conductivity measurements on powders media has been designed and constructed at ENEA CR Brasimone: the Tubes for Powders (TxP) Facility [4]. It consists of three concentric tubes instrumented with forty-eight thermocouples and it relies on two annular gaps of different sizes for conductivity measurements.

The present paper focuses on the experimental campaigns carried in TxP to characterize Si-C and AISI-316 powders in support to the design of the Heavy liquid metal pressurized water cooled tubes (HERO) test section which consists of a bundle of 7 tubes representative of the ALFRED SG (tubes in full scale). The main aims of the experiments are to assess the conductivity of powders both in air environment and in pressurized helium atmosphere.

2 DESCRIPTION OF THE TXP FACILITY

The TxP facility [4] consists of three concentric tubes whose conceptual scheme is reported in Figure 1. The tube labeled as PIPE-5 contains an Heating Rod (HR-14) that generates 25 kW (maximum). PIPE-5 is inserted in PIPE-7 which is contained in PIPE-8. This last tube allows to cool the facility by means of water. Two free volumes are realized in the facility to locate the testing powders. The first is bounded in the annular region HR-14 - PIPE-5 and the second is placed between PIPE-5 and PIPE-7. The intent of the first zone is to obtain fruitful data on conductivity into a large gap (about 15 mm in width) while, the gap between PIPE-5 and PIPE-7, is designed to test powders specimens into a small gap (about 5 mm in width). The main objectives of TxP are:

- Determine the thermal conductivity of candidate powders.
- Determine the influence of the powder compaction grade on the conductivity.
- Investigate the influence of the filling gas (i.e He) at different levels of pressurization.

The design includes 48 N-type thermocouples located in three azimuthal and four axial directions. Twelve are placed at HR-14 outer surface, twenty-four are located in PIPE-5 and the remaining are positioned in the inner surface of PIPE-7. The thermocouples located at the
gap borders allow to measure the temperature difference between the tubes – walls that embed the powders under testing. The thermal conductivity of the powder is calculated by Eq. 1.

$$k_e = \frac{q'I_{\text{ext}}}{2\pi(T_{\text{int}} - T_{\text{ext}})}$$

Equation 1

$q'_{\text{ext}}$ powdered gap outer radius (inner radius of PIPE 5 or PIPE7) [m]
$q'_{\text{int}}$ powdered gap inner radius (outer radius of HR-14 or PIPE5) [m]
$T_{\text{ext}}$ powdered gap outer surface temperature (at PIPE 5 or PIPE7) [K]
$T_{\text{int}}$ powdered gap inner surface temperature (at HR-14 or PIPE5) [K]
$k_e$ powder conductivity [W/m-K]
$q'$ average linear power [W/m]

The quantity $q'$ is obtained measuring the integral power ($q$) with high accuracy by means of a watt-meter WT230 Digital Power Meter. Two additional thermocouples are placed in HR-14. The first is operated to control the facility ($T_{\text{C-HR}}$), the second allows to shut-down the facility if a safety set point is met ($T_{\text{S-HR}}$). The auxiliary systems include: the water line, the helium line, the control cabinet and the data acquisition system, Figure 1. The feed-water main line is connected to the service water by pipes and includes three valves $V_0$, $V_1$ and $V_2$. $V_1$ allows the manual regulation of the mass flow rate [0-12.5 l/min]. The line is instrumented with a flow-meter and four thermo-resistances ($T_{\text{IN}}, T_{\text{H2O-IN}}, T_{\text{OUT}}, T_{\text{H2O-OUT}}$). Two minor pipelines depart from the main line to cool the bottom ($V_{1B}$) and the top ($V_{1T}$) flanges. They are instrumented with two thermocouples ($T_{\text{FT}}, T_{\text{FB}}$).

The helium line includes the helium high pressure tank (200bar) with its pressure reducer and safety valves, pipes, two valves ($V_{1He}, V_{2He}$) and a manometer placed before the valves. When TxP is operated in helium environment it is necessary to remove air from the facility. This is realized by the “washing procedure” that consists in opening $V_{1He}$ ($V_{2He}$ closed) and pressurizing PIPE-5 up to a selected level, closing $V_{1He}$ and opening $V_{2He}$ and repeating the procedure at least ten times. During operation both these valves are closed when a given level of pressure is reached.

The control cabinet regulates the facility by means of power pulses. It is driven by the comparison between the $T_{\text{C-HR}}$ signal and $T_{\text{C-HR-SET-POINT}}$. It automatically shuts-down the facility if $T_{\text{S-HR}}$ meets the $T_{\text{S-HR-SET-POINT}}$. The acquisition system consists of a computer in which MX-100 software is installed. It is able to record data from the signals reported in Figure 1. The geometrical and operational data of the facility are given in Table 1.

**Table 1: Main features of TxP.**

<table>
<thead>
<tr>
<th><strong>TxP geometry</strong></th>
<th><strong>TxP operating conditions</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>HR-14 outer radius</td>
<td>mm 16.0 Water inlet temp. °C</td>
</tr>
<tr>
<td>PIPE-5 inner radius</td>
<td>mm 31.3 Water outlet temp. °C</td>
</tr>
<tr>
<td>PIPE-5 outer radius</td>
<td>mm 36.5 Water mass flow l/m</td>
</tr>
<tr>
<td>PIPE-7 inner radius</td>
<td>mm 42.3 HR power kW</td>
</tr>
<tr>
<td>PIPE-7 outer radius</td>
<td>mm 44.5 Helium pressure bar</td>
</tr>
<tr>
<td>PIPE-8 inner radius</td>
<td>mm 51.1 Maximum HR temp °C</td>
</tr>
<tr>
<td>PIPE-8 outer radius</td>
<td>mm 57.1 Active length mm</td>
</tr>
</tbody>
</table>

Geometry of the gaps in TxP

| HR-14 – PIPE-5 width | 15.3 mm | PIPE-5 – PIPE 7 width | 5.8 mm |
| HR-14 – PIPE-5 free vol. | 3.89 l | PIPE-5 – PIPE 7 free vol. | 2.44 l |
Two different lots of Si-C and one lot of AISI-316 powders are investigated:

- RUN#2: Si-C powder having grain diameter in the range [149-247] μm
- RUN#3: Si-C powder having grain diameter in the range [1-80] μm
- RUN#5: AISI-316 powder having grain diameter in the range [1-200] μm

Two sets of tests are presented in this paper. The first one includes RUN#2, RUN#3. The common objective of these sub-tests is to investigate the conductivity of the Si-C powders both in air and pressurized Helium environment. The second one aims to investigate the thermal conductivity of AISI-316. It includes RUNs#5.1-2-3-4 (air environment) and RUNs#5.5-6-7-8 (helium environment).

All these tests are conducted loading the powder with the standard procedure Double Step (DS) vibrated. It consists in filling the region HR-14 - PIPE-5 outside the facility: PIPE-5 is fixed to a mechanical equipment HR-14 is mounted and the vibration is applied directly on PIPE-5 during the loading. At the end of this first step, PIPE-5 is mounted in TxP and the region PIPE-5 - PIPE-7 is filled with powder while the facility is vibrated on PIPE-8. The influence of the loading procedure is discussed in Ref. [5].

The tests are experienced in un-pressurized air environment or pressurized helium environment in the temperature range [100-450]°C with a temperature increase of 20-30°C. The holding time to achieve steady state condition between two set of measurements was about 15 minutes and the acquisition time was 6 minutes.

The main specifications of the tests are reported in Table 2. The reference density is reported in row (b) with the aim to compare the density achieved into the annular region. It has been estimated weighing the powder into a graduated cylinder of 1 l.
Table 2: RUN#2, RUN#3, RUN#4 and RUN#5, summary of the specifications.

<table>
<thead>
<tr>
<th>#</th>
<th>Description</th>
<th>RUN#2.0 to RUN#2.4</th>
<th>RUN#3.0 to RUN#3.4</th>
<th>RUN#5.0 to RUN#5.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>Theoretical density [kg/dm³]</td>
<td>3.21</td>
<td>3.21</td>
<td>7.96</td>
</tr>
<tr>
<td>(b)</td>
<td>Reference density ¹ [kg/dm³]</td>
<td>0.93</td>
<td>1.13</td>
<td>3.40</td>
</tr>
<tr>
<td>(c)</td>
<td>Estimated density ² [kg/dm³]</td>
<td>0.80</td>
<td>1.17</td>
<td>3.70</td>
</tr>
<tr>
<td>(d)</td>
<td>Loaded powder [kg]</td>
<td>3.04</td>
<td>4.47</td>
<td>14.12</td>
</tr>
<tr>
<td>(e)</td>
<td>Estimated porosity ³ [%]</td>
<td>0.751</td>
<td>0.635</td>
<td>0.535</td>
</tr>
<tr>
<td>(f)</td>
<td>Filling gas</td>
<td>RUN#2.0 Air-He [1-4.5bar]</td>
<td>RUN#3.0 Air-He [1-4.5bar]</td>
<td>RUN#5.0 to 5.4 Air-He [1-4.5bar]</td>
</tr>
<tr>
<td>(g)</td>
<td>HR-14 - PIPE-5 free vol. ⁴ [l]</td>
<td>3.812</td>
<td>3.812</td>
<td>3.812</td>
</tr>
<tr>
<td>(h)</td>
<td>Testing temperature [°C]</td>
<td>100-450</td>
<td>100-450</td>
<td>100-450</td>
</tr>
<tr>
<td>(i)</td>
<td>Temperature increase [°C]</td>
<td>20-30</td>
<td>20-30</td>
<td>20-30</td>
</tr>
<tr>
<td>(j)</td>
<td>Holding time [min]</td>
<td>15</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>(k)</td>
<td>Data acquisition time [min]</td>
<td>6</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>(l)</td>
<td>Material</td>
<td>Si-C</td>
<td>Si-C</td>
<td>AISI-316</td>
</tr>
<tr>
<td>(m)</td>
<td>Grain diameter [µm]</td>
<td>[149-247]</td>
<td>[1-80]</td>
<td>[1-200]</td>
</tr>
</tbody>
</table>

¹→ obtained weighting the powder without vibration into a graduated cylinder of 1 l
²→ obtained as [kg of powder introduced in HR-14 - PIPE-5] / [measured HR-14 - PIPE-5 free volume dm³]
³→ obtained as [1 – (estimated density) / (theoretical density)]
⁴→ measured by injection of water

3.1 Experimental Characterization of Si-C Powder

The post-processing of RUN#2 is reported in Figure 2. The figure includes the experimental data from the five cycles and the average trend of conductivity (with an uncertainty band of ±10%). Si-C powder in the diameter range [149-247]µm highlights an unexpected low conductivity with respect to unpowdered material (which is above 70 kW/m°C). The maximum value is about 0.3 W/m°C which is obtained in He atmosphere at 4.5 bar. In general, the experimental trends are approximately constant with a slight increase with temperature and a large spreading which is due to the fact that these low values of conductivity are close to the accuracy of the measurements (therefore we did not develop correlations). The introduction of He at 1 bar instead of un-pressurized air increases the conductivity of about 40%. The conductivity is found to increase depending on the helium pressure: it results more or less doubled at 4.5 bar when compared to experiment at 1 bar.

RUN#3 is analysed in Figure 3. Si-C powder in the diameter range [1-80]µm confirmed the low conductivity obtained in RUN#2. The maximum value is about 0.5 W/m°C, it is obtained in He atmosphere at 4.5 bar. In general, the experimental trends slightly increase with the temperature.
3.2 Experimental Characterization of AISI-316 Powder

RUN#5.0, RUN#5.1, RUN#5.2, RUN#5.3 and RUN#5.4 address the effect of thermal cycling. They have been conducted under air atmosphere by repeating the same experiment four times after the first load (in RUN#5.0). The main results are depicted in Figure 4. Two correlations obtained by parabolic interpolation have been identified. The first (Eq. 2), is representative of the fresh powder and groups RUN#5.0 and RUN#5.1. The second (Eq. 3), highlights the effect of powder compaction and groups the subsequent tests: RUN#5.2, RUN#5.3, RUN#5.4. This last phenomenon is connected with the increase of grain size [5] induced by the high temperature achieved in previous tests which tends to enhance the thermal conductivity. This last curve ends at 300°C since it was not possible to achieve the target temperature (450°C).

\[
C_{RUN\#5.0-1} = 2 \times 10^{-6}T^2 + 13 \times 10^{-4}T + 0.3601
\]  
\[
C_{RUN\#5.2-3-4} = 9 \times 10^{-6}T^2 - 8 \times 10^{-4}T + 0.5231
\]

The subtests from RUN#5.5 to RUN#5.8 have been conducted using the same sample of powder loaded in RUN#5.0 in order to investigate the effect of helium introduction at different pressure levels once grain growth has saturated. They have been conducted under helium atmosphere at four different pressures: 1, 2, 3 and 4 bar. The experimental findings are reported Figure 5. The figure includes a correlation obtained by parabolic interpolation for each test (reported from Eq. 4 to Eq. 7). As in the case of Si-C, it is possible to increase the conductivity up to a value that is about 400% greater than the maximum value measured for Si-C by pressurizing the facility. Therefore, it has been decided to load the HERO SG unit with AISI-316 powder instead of Si-C.

\[
C_{RUN\#5.5} = C_{He-1\text{ bar}} = 9 \times 10^{-6}T^2 - 9 \times 10^{-4}T + 1.0963
\]
\[
C_{RUN\#5.6} = C_{He-2\text{ bar}} = 7 \times 10^{-6}T^2 + 2 \times 10^{-4}T + 1.112
\]
\[
C_{RUN\#5.7} = C_{He-3\text{ bar}} = 7 \times 10^{-6}T^2 + 2 \times 10^{-4}T + 1.2412
\]
\[
C_{RUN\#5.8} = C_{He-4\text{ bar}} = 5 \times 10^{-6}T^2 + 8 \times 10^{-4}T + 1.3198
\]
DISCUSSION

In order to explain the unexpected behaviour of Si-C, a sample of powder from RUN#2 has been compared with a sample of powder of AISI-316 heated at 400°C for 24 hr by SEM examination. The pictures are given in Figure 6. Compared to AISI-316, it is qualitatively evident that Si-C grains have larger surface porosity (open porosity) that causes reduction of contact points among the particles. This is reflected in strong degradation of the conductivity. Therefore, when assessing further materials for conductivity measurements, a preliminary analysis by SEM (with resolution 1000x) is recommended to check the powder structure in order to avoid materials that are similar to Si-C.
5 CONCLUSIONS

The TxP facility was constructed and operated by ENEA with the aim to qualify porous heat transfer enhancer materials for the application to double wall bayonet tube steam generators such as those identified for the ALFRED reactor. The activity supported the design and construction of seven prototypic double wall bayonet tubes (full scale with respect to ALFRED): the HERO test section. At the beginning, the candidate material was SiC powder and its alternative was AISI-316 powder.

The experimental findings highlight these main conclusions:

- Si-C powder revealed an extremely low conductivity with respect to the dense material. This seems to be related to its large open porosity.
- AISI-316 powder behave better that Si-C (even if the solid material has lower thermal conductivity).
- AISI-316 powder conductivity was sensitive to thermal cycling being this effect beneficial to this property.
- AISI-316 powder conductivity increased in He environment and with its pressure level.

This last powder was selected as material for the construction of the test section (under He atmosphere at 4.5bar), even if further materials deserve to be analyzed to find out a heat transfer enhancer suitable for the ALFRED SG. In fact, preliminary calculations evidenced that AISI-316 powder will affect the super-heated steam outlet temperature of about 25°C compared to the design of ANSALDO (which assumes 55 times the conductivity of He as indefinite porous medium).
REFERENCES


