Characterization of the thermal conductivity for ceramic pebble beds

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Abstract. The evaluation of the thermal conductivity of breeder materials is one of the main goals to find the best candidate material for the fusion reactor technology.
The aim of this paper is to evaluate experimentally the thermal conductivity of a ceramic material by applying the hot wire method at different temperatures, ranging from 50 to about 800°C.
The updated experimental facility, available at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, used to determine the thermal conductivity of a ceramic material (alumina), will be described along with the measurement acquisition system. Moreover it will be also provided an overview of the current state of art of the ceramic pebble bed breeder thermos-mechanics R&D (e.g. Lithium Orthosilicate (Li_4SiO_4) and Lithium Metatitanate (Li_2TiO_3)) focusing on the up-to-date analysis.
The methodological approach adopted is articulated in two phase: the first one aimed at the experimental evaluation of thermal conductivity of a ceramic material by means of hot wire method, to be subsequently used in the second phase that is based on the test rig method, through which is measured the thermal conductivity of pebble bed material. In this framework, the experimental procedure and the measured results obtained varying the temperature, are presented and discussed.

1. Introduction

An open issue for fusion power reactor is the possibility to obtain Tritium in the breeding blanket. The envisaged solution, as known in the scientific literature [1-2-3], foresees the use of pebble beds made of ceramic materials such as lithium orthosilicate (Li_4SiO_4) or lithium metatitanate (Li_2TiO_3), etc. which could also allow to slow down neutrons and extract thermal power.

The pebbles will be loaded into a box-like structure, therefore they must be able to support severe conditions foreseen for the breeding blanket (cyclic mechanical stresses, high temperature and high thermal gradients, irradiation effects) and must exhibit long-term thermo-mechanical stability, and a sufficient compatibility to the adjacent structural materials and low activation levels.

A lot of research effort [1-10] has been spent in developing a thorough understanding and characterization of the pebbles bed, particularly from a thermo-mechanical point of view. Specifically the knowledge of the effective thermal conductivity of pebbles is essential for a proper thermo-mechanical blanket design [6] and assessment of the heat transfer processes.

The research program, developed at the Department of Civil and Industrial Engineering (DICI) of the University of Pisa, aims at characterizing the effective thermal conductivity (λ) of pebbles bed at different temperatures and for compression forces up to 100 kN [8-13].

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To the purpose, the methodological approach used, and described extensively in [2], is based on the evaluation of the effective thermal conductivity of pebbles by means of the hot plate with guardian ring method. The effective thermal conductivity (λ) of pebbles bed is therefore calculated in steady state condition by measuring the thermal gradient through an alumina disc (ceramic material) and the pebbles bed [11-12].
Moreover to attain that purpose, the thermal conductivity of the alumina have been experimentally determined by executing hot wire tests on an alumina cylinder for temperatures ranging from 20° to 800°C.

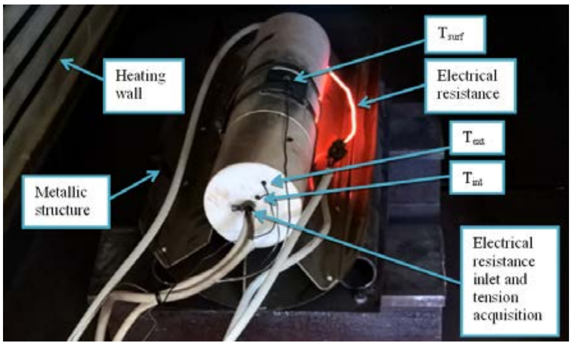
In this paper the experimental activity described refers mainly to the second series of experiments carried out at the Laboratory Scalbatraio of DICI of the University of Pisa.
The results obtained will be presented and discussed in what follows.

2. Description of the experimental facility

The experimental device adopted to execute the hot wire tests consists of (Figure 1):

- Alumina cylinder;
- Oven;
- Thermocouples and electrical resistance;
- Fan-inverter and
- Data Acquisition System (DAS).

The alumina cylinder is made of Alubit 90 (90 wt% Al_2O_3), which has the same composition and was produced with the same technological process of the alumina disk used in the measuring cell of the hot ring method device. It is 280 mm long (L) and has 35 mm radius.
The alumina cylinder has three holes: the first is located in the centre of the cylinder, the second and the third are located at different radial distances from the symmetry axis. Moreover, the central hole allows housing the electrical resistance, while in the other two holes, at 7.75 mm (r_{int}) and 21.2 mm (r_{ext}) from the centre, type K thermocouples are accommodated.
These thermocouples allow to measure the temperature (T_{int} and T_{ext}) inside the cylinder, while the thermocouple (T_{sur}) welded on a thin copper plate, which is placed on the external surface of the cylinder as shown in Figure 1 a, allows to measure the superficial temperature of the specimen itself.
Moreover, a metallic support structure sustains the alumina cylinder and avoids the contact between the specimen and the oven surface.



(a)

(b)

Figure 1. a) Alumina sample equipped with thermocouples and resistors, and b) the complete experimental apparatus with Fan-Inverter system and DAS.

The oven has all surfaces radiating, during the heating, except the tailgate. It is equipped with a Gefran© GF_Promer, a graphic set-point programmer that provides an accurate configuration of the temperature through a PID controller.

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An advanced tuning control allows to check the best PID parameters. The initial conditions of the oven are set up in order to obtain a heating rate of 1°C/1.5 min (assumed increment of oven temperature into the PID) until the desired test temperature was reached.
During tests, the following parameters have been recorded:

- The potential difference across the resistance;
- The voltage drop across the shunt and, based on that, the resulting current;
- The power;
- The alumina temperature through the thermocouples;
- Oven and air temperatures.

Wires and thermocouples are connected to the National Instruments Acquisition System (SCXI1000) that provides directly output data on a pc through LabView software. Additionally, as indicated in [12], to properly determine the thermal conductivity of the alumina specimen, the power generated by the electrical resistance has been removed by forced convection.
The fan (previous Figure 1 b) used to that purpose, has been duly supported to guarantee the parallelism of the tube with the ground; moreover it has been connected to an inverter in order to obtain a more precise regulation. This tube by connecting the fan to the oven conveys the air directly on the outer surface of the alumina.

It is important to remark that the forced convection (operation of the cooling fan-inverter system) has been used for temperatures below 450°C; for higher temperatures (up to 800°C) the radiant heat transfer is considered to be sufficient to remove the power generated by the electrical resistance and to reach accordingly a steady state condition.

2.1 Description of the tests executed

To carry out experimental tests, an already proven procedure has been used [12]. It may be specifically summarised in the following main steps:

1. The alumina specimen is firstly put on the metallic support onto the oven surface;
2. The temperature is set at the desired test value;
3. The oven is turned on and heated up to the set temperature;
4. If the test temperature is below 450°C, the cooling fan is turned on to allow to homogenize the temperature inside the oven chamber;
5. When temperature reaches the set value and stabilises around it (see the yellow behaviours in correspondence of TEMP_EXT_CH1 and TEMP_INT_CH2 indicated in Figure 2), the steady state condition is reached;
6. Data acquisition begins from this instant and lasts for at least 300 s.

Based on the data measured, the thermal conductivity is determined accordingly to the following formula:

$$\lambda_A = \frac{\phi_0}{2 \cdot \pi \cdot \Delta T \cdot L} \ln\left(\frac{r_{ext}}{r_{\text{int}}}\right) \tag{1}$$

where Φ_o is the power of the electric resistance, ΔT is the temperature difference between T_{int} and T_{ext} measured at the two radii r_{int} and r_{ext}, L is the length of the electric resistance.

The thermal conductivity resulted so dependent on Φ_o and ΔT being fixed the two radii and the resistance length L (the geometrical parameters may be considered constant).

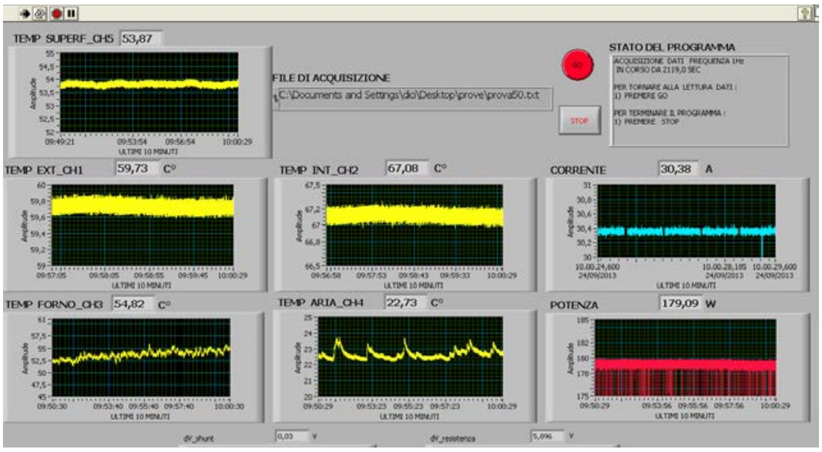

Figure 2. Overview of the test parameters acquired by DAS (through Lab View interface).

2.2 Discussion

Several tests have been performed into the range from 50°C to 800°C, with increment of 50°C.
In the following Figure 3 and Figure 4 the plots of the temperatures vs. time obtained carrying out wire tests respectively at 200°C and 500°C, are showed. Moreover in Figure 4 is indicated the instant at which the oven (indicated as electrical resistance) and the fan are turned on.
As shown the steady state condition is achieved by means of the fan regulation (by inducing a forced convection) in the first case, while in the second one, as previously mentioned, the radiant heat transfer is sufficient to remove the amount of heat generated in the alumina centre. In this latter case (like in Figure 4) the steady state condition is reached with a longer time interval, due to the energy balance between the radiant heat transfer and the heat of the resistance.

Specifically, the results show that at an average temperature of 200°C (Figure 3), with an average power of 162 W and a differential temperature (between the internal and external thermocouple) of 7.3°C, the thermal conductivity of alumina is 12.67 W/m°C. Furthermore, at an average temperature of 523°C, with an average power of 181 W and with a differential temperature of 13°C, the thermal conductivity of alumina is 7.96 W/m°C (Figure 4).

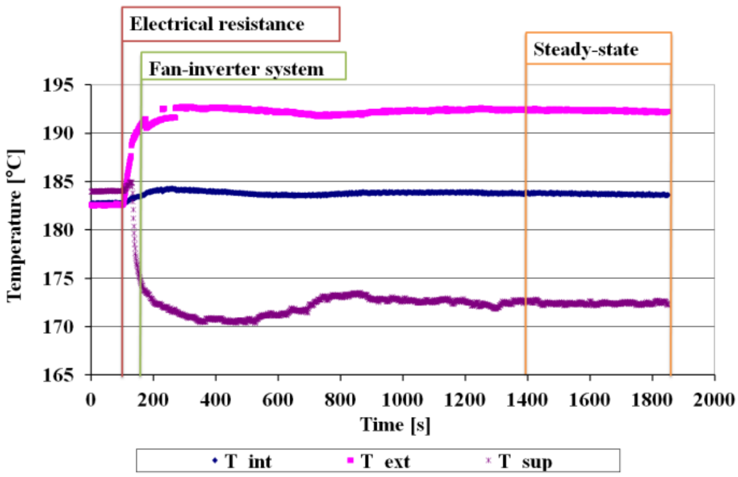

Figure 3. Hot wire test results at 200°C.

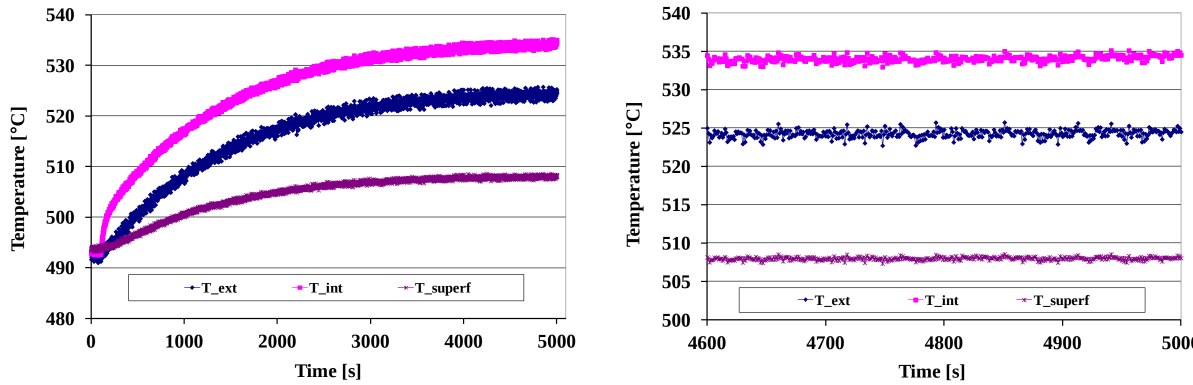

Figure 4. Hot wire test results at 500°C.

The wire tests were repeated several times; for each test campaign the calibration of thermocouples was also repeated: the mean error related to the measure resulted about 4 %.

The trend of the alumina thermal conductivity versus temperature, as experimentally calculated, is shown in Figure 5.

Analysing this behaviour, it is possible to observe that the conductivity decreases along with the increase of the test temperature. The maximum standard deviation is 5 %, as clearly recognizable from the bars of the error depicted in Figure 5: the experimental data have been also interpolated with a fifth-order polynomial curve (indicated with the dark line in Figure 5).

Analysing the results fit very well the interpolation curve even if some spreading appears at low temperature. Moreover analysing the λ behaviour, it is possible to observe that the thermal conductivity decreases along with the increase of the test temperature.

This outcome, in line with the expected results, confirms the trend observed in the first experimental campaign [12] carried out at the DICI of the University of Pisa. The thermal conductivity decreases when temperature increases, and this result agrees with the data available in literature.

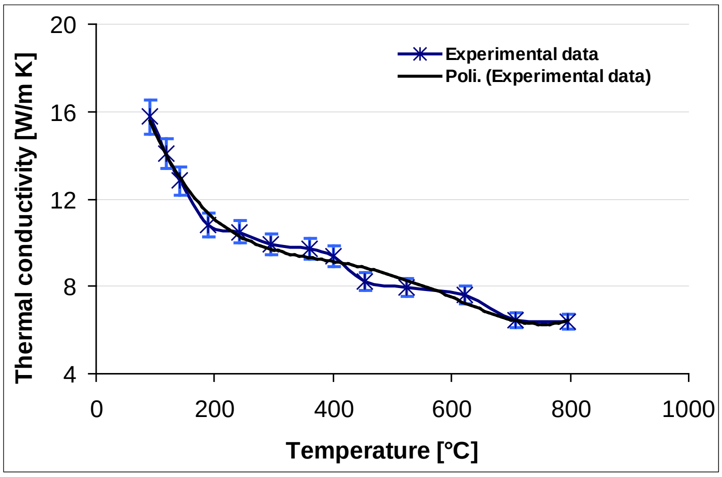

Figure 5. Thermal conductivity vs. temperature.

Figure 7 shows the comparison of the alumina thermal conductivity vs. temperature obtained in both the first (2014) and second experimental campaign: λ values in the former are indicated with the red triangle squared point, while in the latter (2015) with blue point.

The comparison of these curves, represented with a proper interpolation curve, highlights a good agreement despite some singularity at lower temperature (at 60°C the discrepancy is about 9%).

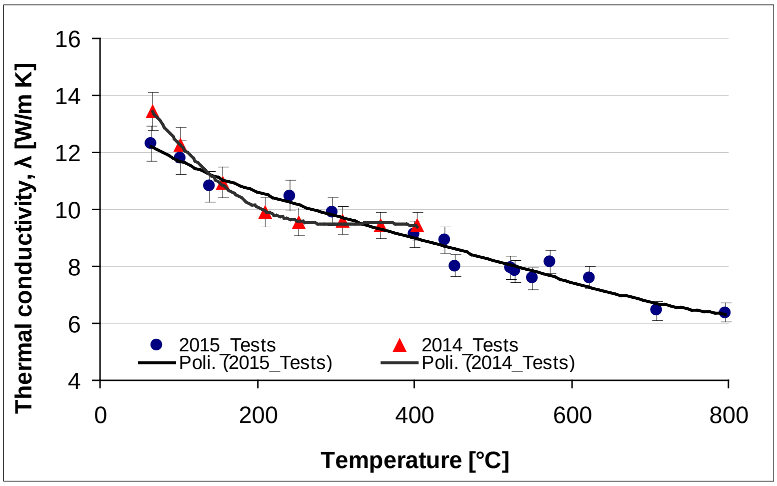

Figure 6. Experimental λ values**.**

Finally the values of the alumina thermal conductivity have been compared to those available in literature. Figure 8 shows that λ values have a similar trend to that of Bansal and Zhu [14] with a quite better agreement at higher temperature (T > 350°C). Once more, even if the discrepancy observed is about 10-15%, it could be explained by considering the different material composition of the specimen used to execute tests (alumina 100%wt compared to Alubit90) and could also rely on the different test conditions for which no accurate description is given in [14](leak in literature data).

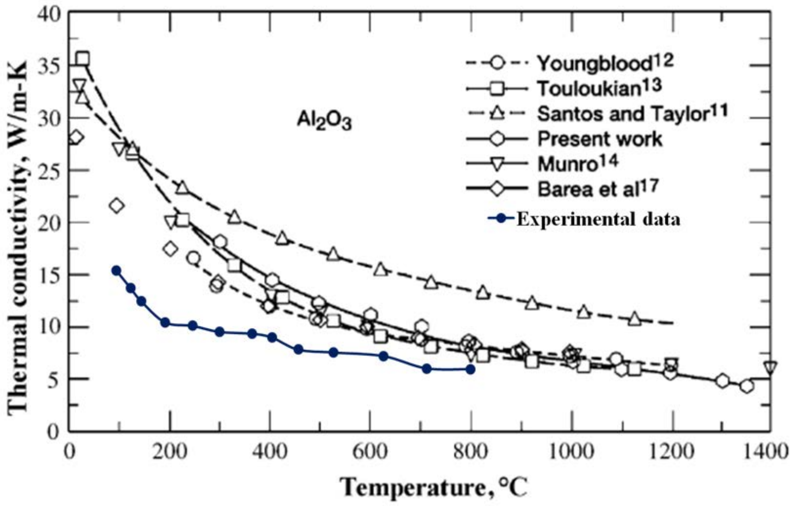

Figure 7. Comparison between literature and experimental alumina thermal conductivity.

3. Conclusions

The determination of the thermal conductivity of breeder materials is one of the main goals to find/select the best candidate material for the fusion reactor technology.

In this paper the thermal conductivity of the alumina, to be used as reference thermal conductivity in the hot plate with guardian ring method, has been determined by performing hot wire tests at different temperatures.

The thermal conductivity of an alumina cylindrical specimen has been calculated at stationary conditions (lasting at minimum 5 minutes) on the basis of the temperature gradient measured by thermocouples positioned at two different radii from the central axis.

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The experimental activity (second test campaign) was carried out at the Lab. Scalbatraio of the Dep. DICI of the University of Pisa by using a dedicated device and an adequate DAS.

Hot wire tests have been executed in the temperature range 50÷800°C, with increment of 50°C.

The results show, as an example, that at an average temperature of 200°C, the thermal conductivity of alumina is equal to 12.67 W/m°C, whereas at about 550° it is 7.96 W/m°C.

Analysing the λ behaviour, it is possible to observe that the conductivity decreases as the test temperature increases: the calculated maximum deviation is less than 5%. Results fit very well the interpolation curve even if some spreading appears at low temperature.
Moreover analysing the λ behaviour, it is possible to observe that the results confirms the trend observed in the first experimental campaign.

A further comparison with the data available in literature (e.g. Bansal, D. Zhu, 2005) highlights a similar trend, despite some discrepancy at lower temperature that could be probably due to the different material composition and test condition.

The alumina thermal conductivity will be used subsequently as reference value for the investigation of the thermo-mechanical characterization of ceramic pebble beds of interest for the breeding blanket (this activity is currently ongoing at the DICI- University of Pisa).

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