EXPERIMENTAL INVESTIGATION OF STEADY STATE RADIAL HEAT FLOW TO MEASURE EFFECTIVE THERMAL CONDUCTIVITY OF CERAMIC PEBBLE BED

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Abstract: *Lithium-based ceramics have been considered as a tritium breeder material in the breeder blanket in the fusion reactors as a pebble bed. Pebbles beds are proposed because of their properties such as high surface area, porosity, ability to get filled in complex shapes, resistance to thermal expansion and fatigue strength. It is very essential to study the thermal characterization of this material as a pebble bed subjected to fusion relevant conditions. The effective thermal conductivity of a packed bed is one of the important parameters for the design of the breeder blanket modules of a future fusion reactor. The pebble bed of Li2TiO3 pebbles (1 ± 0.15 mm diameter) packed with 62-63% packing fraction, were used as test samples in the experiments. The effective thermal conductivity was measured as a function of mean bed temperature in the range of room temperature to 120 `C using 1 ± 0.15 mm diameter* Li_2TiO_3 *pebbles. A clear dependence of the effective thermal conductivity on the mean bed temperature of the pebble bed was observed. Experiments were performed in helium atmospheres in the pressure range of 0.05 bar to 3 bar gauge pressure. The effect of pressure variation on the effective thermal conductivity of pebble bed was investigated for the range of 0.05 bar to 3 bar gauge pressure using 1.0 ± 0.15 mm diameter* Li_2TiO_3 *pebbles. Effective thermal conductivity of pebble bed was found to be increased with the increase of pressure while using helium as filling gas over a temperature range of room temperature to 120 `C. The effect of pressure change was found to be more significant in the pressure range of 0.05 bar to 1 bar gauge pressure.*

Keywords: **Pebble Bed, Thermal Conductivity, Fusion Technology, Heat Transfer**

1. INTRODUCTION

Nuclear energy is the core of interest for many research organizations globally. There are two types of processes in nuclear science which release energy from atoms, nuclear fission and fusion. In the Fission process atom with a high atomic number is split into two or more atoms with lower atomic numbers. When two atoms with a lower atomic number fuse and produce one atom with a higher atomic number, the reaction is called a fusion reaction. Fuel is in the state of plasma at a temperature where fusion can be achieved. Plasma is an electrically neutral hot ionized gas, where electrons are completely free from the positive nucleus. It is also known as the fourth state of matter. But creating and handling plasma state of matter is difficult however it is necessary for the fusion process. Lithium ceramic pebbles are the most promising candidates for tritium breeding material in future fusion reactors. Indian LLCB module consists of a pebble bed made of Li_2TiO_3 solid pebbles with approx. diameter of 1 mm and helium as purging gas. In the fusion environment, it will face severe conditions, like neutron radiation, high temperature, thermal expansion, and high heat flux. Because two materials present with distinct phases in the pebble bed it will show very complex thermomechanical behavior. Hence the effective thermal conductivity of the pebble bed also depends on thermomechanical behavior of both materials, Li_2TiO_3 and helium gas. This work aims to design and develop an experimental test facility based on Steady- State Radial (SSR) direction heat flow method to measure the effective thermal conductivity of the ceramic pebble bed as a function of purging gas, temperature and pressure. The scope for the investigation is to optimize parameters of the experimental setup, increase test sample size, reduce metal influence in the pebble bed, examining at higher temperature and pressure. Measure the effective thermal conductivity with flowing gas condition. And make one more step toward more accurate measurement of the effective thermal conductivity of a pebble bed.

2. Literature Review

2.1. Parameters affecting the effective thermal conductivity of the pebble bed

Thermal conductivity of pebbles, thermal conductivity of filling gas, gas pressure, bed deformation and pebble ped packing fraction are main affecting parameters for effective thermal conductivity of the pebble bed. Several researches were conducted on these parameters and their effects.

2.1.1. Conductivity of Pebbles

A study conducted by M. Enoeda [1] on a group of lithium ceramics showed that the effective conductivity of the pebble bed is directly proportional to the conductivity of pebbles. In study effective thermal conductivity of Li_2O pebble bed was found higher than Li_2TiO_3, Li_2ZrO_3 and Li_4SiO_4 pebble beds. Because Li_2O has higher thermal conductivity than all these lithium ceramics.

2.1.2. Conductivity of Gas

A study carried out by A. Abou-Sena [2] reported the effect of thermal conductivity of filling gas on effective thermal conductivity of the pebble bed. In study, measurements were taken with vacuum, nitrogen, air and helium as filling gas. Lowest value of effective thermal conductivity for the pebble bed was obtained with vacuum and highest with helium. While values with air and nitrogen were observed between those. The reason is helium has higher thermal conductivity than air and nitrogen. This study verified direct proportionality between the thermal conductivity of gas and the effective thermal conductivity of the pebble bed.

2.1.3. Gas Ratio of Solid to Gas Conductivity

Pebble beds are made of two materials: solid pebbles and gas (filled in voids). Both of these have a direct proportional impact on the effective thermal conductivity of pebble beds. Therefore, the ratio of thermal conductivity of solid pebbles to the thermal conductivity of filling gas (ks/kg) should be regarded as an important parameter. As per the study of A. Abou-Sena [3] this ratio plays an important role in the heat transfer through pebble beds. If the value of ks/kg is between 2 to 15 then heat flux tends to be more uniform in both regions, solid and gas.

2.1.4. Gas Pressure

Study of 0.25 mm to 0.6 mm Li_4SiO_4 and 1 mm Li_2ZrO_3 pebble beds were carried out by M. Enoeda [1] to determine the effect of helium pressure on effective thermal conductivity of pebble beds. Another investigation by J. W. Earnshaw [4] on Li_2ZrO_3 pebble bed showed an increase in effective thermal conductivity of the pebble bed by approx. 1.9 times while pressure increased from 4 to 100 kPa. In M. S. Tillack [5] research on binary pebble bed (0.1 & 4 mm) of aluminium and helium recorded 2 times increase in effective thermal conductivity of pebble bed with increase of pressure from 0.1 to 4 bar. Usually, molecular theory for gases states that the thermal conductivity of gas is independent of pressure. But if gas-filled into confined space, where the gap and mean free path of molecules are of the same order, it depends on pressure. In a recent study, S. Pupeschi [6] investigated the effect of gas pressure above atmospheric pressure. The effective thermal conductivity of the pebble bed (Li_4SiO_4 + 20% Li_2TiO_3 by mol) was reduced by around 10% with pressure reduction of helium from 0.4 to 0.12 MPa. Although with air this pressure dependency of the effective thermal conductivity of the pebble bed decreased.

2.1.5. Bed Packing Fraction

Packing fraction shows the percentage of volume utilized by solid material (pebbles) in a container. It has a significant impact on the effective thermal conductivity of the pebble bed. A recent study by M. Enoeda [7] noted that effective thermal conductivity of Beryllium- Helium pebble bed is directly proportional to the bed packing fraction. However, bed packing fraction depends on several factors, like packing technique, pebble bed arrangement (single or binary size), pebble size relative to bed size and range of pebbles. It has been confirmed that the diameter of the container should exceed 10 times the diameter of pebbles to ensure a reliable packing fraction of around 62% [3].

2.2. Steady State method for measurement of thermal conductivity

In steady state methods, the thermal gradient is produced by supplying constant heat flux on the material and measurements are taken after thermal equilibrium is reached. After that, using the Fourier law of 1-D heat flux, the thermal conductivity of the material is determined. Fourier law is the constitutive equation for thermal conduction [8].

2.2.1. Comparative Cut Bar

The sample specimen of definite thickness is placed between two identical reference specimens of known thermal conductivity and thickness [9]. This gathered assembly is placed between two heaters to generate a temperature gradient. To create heat flow in one direction, assembly is enclosed by insulation or heaters. The schematic of the test arrangements given in Figure 1.

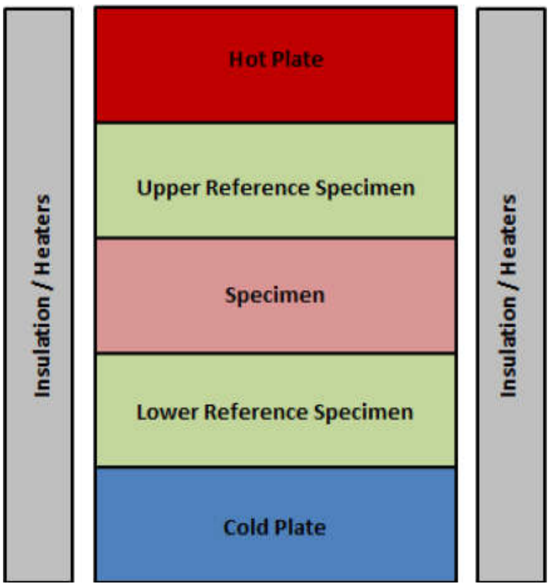

Figure 1. Schematic of Comparative Cut Bar Method

In the above assembly, both reference specimens and the test sample should be equipped with at least two thermocouples at known locations. And if possible, use three to confirm linearity of the temperature gradient. By measuring the temperature gradient in reference specimens of known thermal conductivity, heat flux passing through the test assembly can be determined.

2.2.2. Heat flow meter technique

Assembly consists of a test sample placed between two parallel temperature-controlled heaters, kept at constant temperatures. Heat flux flowing through the assembly is measured using a calibrated heat flux transducer, which is placed along with a test sample as shown in Figure 2. Once thermal equilibrium reached, temperature gradient measured with the help of thermocouples placed at known locations. This method is suggested in ASTM standards for measurements of thermal conductivity [10].

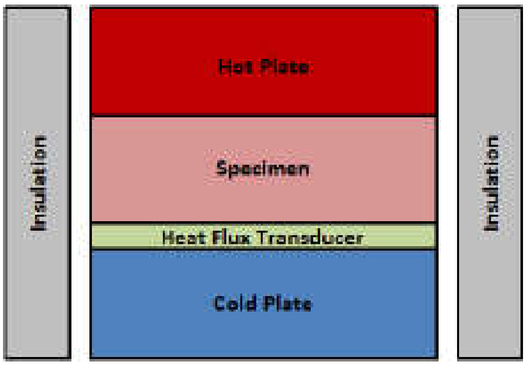

Figure 2. Schematic of Heat Flow Meter Technique

2.2.3. Guarded hot plate technique

This technique can be applied either in two-sided or one-sided mode. In a two-sided arrangement, two identical test specimens arranged symmetrically on both sides of the main heater as presented in Figure 3. And this test assembly is fixed between two cold plates held at a lower temperature than the main heater [11]. While in single side configuration assembly is placed between the main heater and cold plate [12]. But in both forms, guard heaters are used to minimize lateral heat flow. In addition to this one guard heater is used in one-sided arrangement to form an adiabatic surface on the backside of the main heater. Heat flux calculated as the ratio of power generated by the main heater and its surface area. After thermal equilibrium, the temperature gradient is measured by thermocouples installed in the test sample at known locations.

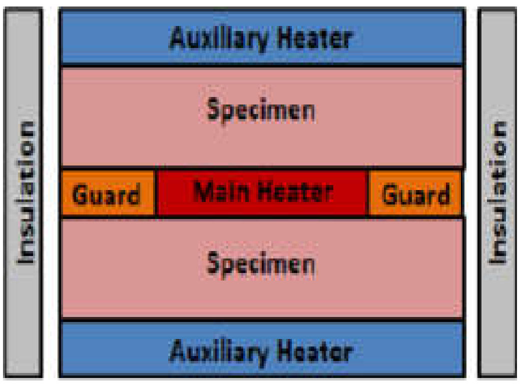

Figure 3. Schematic of Guarded Hot Plate Method

2.2.4. Radial heat flow method

Unlike other steady-state methods, in this technique heat flows in a radial direction. From the center of cylindrical geometry to outward direction. A cylindrical shaped heater is placed at the center of cylindrical geometry and surrounded by the test sample to be examined [13]. Additional band heaters are wrapped outside of geometry to heat the sample for testing at elevated temperatures. Heat flows from the main heater goes to the surrounding or sink if provided as shown in Figure 4. The experimental apparatus can be developed with or without the band heater according to the necessity of testing. Once the desired temperature of assembly is achieved by band heaters, the main heater is energized to produce a temperature gradient along the radial direction in the specimen.

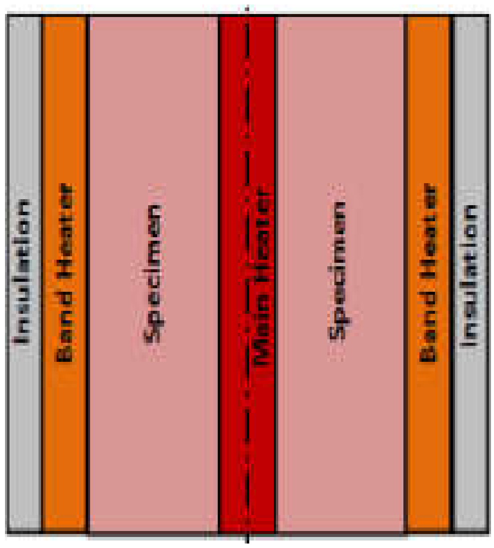

Figure 4. Schematic of Radial Heat Flow Method

3. METHODOLOGY

3.1. Selection of Materials

After completing the literature review and study of existing facilities, the SSR method was chosen for the design of new apparatus. Pebble bed will be created by confining space inside the cylinder with the help of supporting disks. So, material used for these two have extremely significant influence on the design of the apparatus. It could bear high temperature around 900 °C. Without showing any major changes in thermo-mechanical properties. There should be no heat flux along the direction of the cylinder axis. Hence material for supporting disks of the pebble bed should have the lowest possible thermal conductivity. Furthermore, it has to sustain high temperature. And thermal expansion should be negligible. Type – K thermocouples were selected for temperature measurements. It is made of chrome (90% nickel, 10% chromium) as anode and alumel (95% nickel, 2% aluminum, 2% manganese and 1% silicon) as a cathode. Type-K thermocouples are the most common general- purpose thermocouples. It has nearly linear response with increase in temperature and good sensitivity. Guiding tubes for thermocouples, current wires and voltage ties are required to be sealed for maintaining vacuum or pressure state inside the apparatus. For this purpose, soft, deformable and elastic material is needed. Which can fill gaps while tightening. Viton rubber is best for this purpose. Insulating material should not be compromised during high-temperature tests. Also have to serve purpose throughout the experiment. For this reason, alumina tubes were chosen. It is a ceramic and used for insulation purposes in high-temperature furnaces in industries. Alumina tubes can work with 1800 °C temperature and have high corrosion resistance. At the axis of the cylinder, a wire of 0.5-1 mm diameter serves the purpose of the main heater of the SSR apparatus. And voltage ties provided to measure voltage drop along the length. This ultimately used to determine heat released inside the pebble bed. Material of heater wire should have high ohmic resistance, high melting point, high corrosion resistance and low thermal expansion coefficient. Furthermore, fair strength is required to hold the wire straight.

3.2. Optimization of Parameters

Adoption of parameters such as the diameter of pebble bed, length of pebble bed, heating length of band heaters, free length between flanges and band heaters etc. require detailed examination for more conventional design of the test facility. For selection of parameters of the pebble bed, there are certain conditions to examine. Length and diameter of the pebble bed are the most critical parameters. As per theoretical assumption, there should be no heat flux in the axial direction of the pebble bed. But, heat flux in axial direction increases with the increase in diameter of the pebble bed and decreases with the increase in length of the pebble bed. Ultimately it depends on the relative value of the length and diameter of the pebble bed. And for that reason, the ratio of length and diameter (L/D ratio) is used as a parameter to optimize axial heat flux. Supporting disks are required to insert from both sides to create the pebble bed. To keep supporting disks at the exact position every time, proper arrangement is necessary. Therefore, the diameter of supporting disks is made slightly larger than the pebble bed. For that reason, the diameter of the cylinder is also enlarged by 3 mm, from both ends till the pebble bed ends. Because of the larger diameter than pebble bed supporting disks can rest on the ends of the pebble bed. For confirmation of a uniform heating zone, thermocouples are required to place at different heights in the pebble bed. These thermocouples are used to generate a temperature profile along the axis of the pebble bed. For this reason, 5 thermocouples are allocated at 30 mm apart from each other. For calculation of the effective thermal conductivity at least 3 thermocouples are required to place at different radial distances. These 3 points are needed to confirm a straight line in the plot. Therefore, 2 sets of 4 thermocouples at different radial locations are finalized. So, there are 2 thermocouples at the same radial distance for comparison of readings. To finalize positions for these thermocouples FEM simulation is done. Detailed report of analysis is given in Appendix II. Conclusion from this study says that thermocouples should be placed after 10 mm radial distance from the axis. However, to avoid the curvature effect of cylindrical shape some distance from the outer surface must be kept. And one more thing to concern is no two thermocouples should come in line with the axis. So, at last 10, 13, 16 and 19 mm of radial distance is chosen. Arrangements of band heater and heating length of band heater plays an important role to achieve stagnant temperature throughout the pebble bed. FEA simulations and experimentations on THW apparatus concluded precious results on band heater arrangements. Conclusions from his study are as follows (1) In single zone heating arrangements temperature difference between center of pebble bed and 50 mm above was found 74 °C. Temperature of the center was 900 °C. It shows a parabolic temperature profile throughout the pebble bed due to heat loss from the top and bottom (2) In a three-zone heating arrangement one band heater covering 60% heating length placed between two small band heaters. By setting top and bottom band heaters at a little higher temperature than the middle heater, it reduced the temperature difference throughout the pebble bed to 7 °C. Almost linear temperature profile (3) Heating length of band heaters must be 1.5 times larger than the length of the pebble bed to get uniform temperature throughout.

4. EXPERIMENTATION AND RESULTS

Assembly process of the SSR apparatus is quite long. In the first place, all wires are prepared. After that pebble filling and joining of components are done. And at last, all vents are sealed. Now the setup is ready for an experimental run. There are 3 different sets of wires needed for the SSR apparatus. And they have some requirements that must be satisfied. This step includes preparation of the heater wire, voltage ties and connecting wires. The heater wire and voltage ties are the first thing to be ready. So, wire preparation is the first step. The heater wire required to be straight and uniform diameter throughout the pebble bed. Kanthal wire with 0.8 mm diameter is used for this purpose. First wire is stretched while passing high ampere current to make it straight. The heater wire is required to fit between both supporting disks and it will be connected to copper wires with help of connectors. So, the length of the heater wire should be exact otherwise it will bend inside the pebble bed. Once the heater wire is ready the voltage ties of the same wire are made by wounding on it. Purpose of voltage ties is to give a voltage drop of the length between them. However, Kanthal has uniform resistance throughout the length and also, we need heat flux in the uniform temperature zone of the pebble bed only. So, voltage ties on the heater wire are made 110 mm apart, which makes it easy to handle it. In this step, the pebble bed is formed for the experimentation. First, current and voltage tie wires are passed through holes in the top supporting disk. Now all radial thermocouples are passed through their dedicated holes. And the top supporting disk is inserted into the test cylinder till the cut slot. Next all thermocouples and wires are fixed with help of alumina tubes and connectors to keep it straight. At last, Li_2TiO_3 pebbles are poured from a 5 mm diameter hole in the supporting disk with the help of a funnel.

4.1. Experimental Procedure

From the starting of the experimental run to record readings and shut down the system, the following listed steps are performed subsequently. First, a rotary pump connected to a bellow is started and then the ball valve is opened for rough vacuum inside the apparatus. After 5 minutes first, the ball valve is closed and then after the rotary pump. Connection with Helium cylinder is established with PU pipe. Helium supply is turned on, and filled apparatus with helium at a higher pressure than the atmosphere. After that valve is closed and the connection to the helium cylinder is removed. PID controllers, DAQ system and DC power supply system turned on. For higher temperature run band heaters are first switched on and wait for the system to achieve steady-state condition. For RT run this step is avoided. DC supply to the heater wire is turned on and temperature readings of all thermocouples are observed. Once the steady-state condition is achieved temperature readings of all thermocouples and voltage drop from voltage tie are noted down for further evaluation. Then after band heaters, DC power supply and DAQ system are turned off first. And left the system for cooling down. Preparation of the bottom flange is the second step in assembly and very important. First, the heater wire and voltage ties with the bottom supporting disk are inserted in their dedicated tubes from the inner part of the flange. Then after all radial thermocouples are inserted in their tubes from outside, so the connecting pin of thermocouples stays outside.

4.2. Results and Discussion

Experimental runs were performed with Helium al filling gas at room temperature and higher temperature with help of band heaters. A preliminary experimental run and calculation are presented for the understanding of the process. This preliminary run was performed with Li_2TiO_3 pebbles of ~1 mm diameter with 12% porosity and helium as filling gas at RT. After the steady-state condition achieved all necessary parameters required for calculation are listed down. In Table 1 all taken measurements are shown. This preliminary run is for exercise and find out possible difficulties in experiment. Also, it helps to get better idea to optimize experimental procedure. After this preliminary run keff of Li_2TiO_3 pebble bed is investigate for different mean bed temperatures and different helium pressures. Packing fraction (PF) of the pebble bed is percentage of volume which actually occupied by Li_2TiO_3 pebbles. These pebbles have porosity of 12% which also eliminated in this value. Here plot of temperature vs ln (r/R) is shown in

Figure 5, so here the slope for calculation of effective thermal conductivity of the pebble bed is 10.338. After calculation of the preliminary run the value of effective thermal conductivity of pebble bed is 0.8305 W/mK. Parameters such as volume of pebble bed, volume of heater in pebble bed, true volume of pebble bed, packing fraction and heat release per unit length is important listed in Table 1.

Table 1. Readings of Preliminary Run

Description	Value
Mass of pebbles filled	0.4744 kg
Helium pressure inside cylinder	0.110 MPa
Direct current supplied to heater wire	4.5 A
Voltage dropped across the length of voltage ties	1.3187 V
Temperature at radial distance 10 mm	65.44 °C
Temperature at radial distance 13 mm	63.01 °C
Temperature at radial distance 16 mm	60.56 °C
Temperature at radial distance 19 mm	58.89 °C
Volume of pebble bed	254469 mm^3
Volume of TC in pebble bed	1005.31 mm^3
Volume of Heater in pebble bed	80.4248 mm^3
True Volume of pebble bed	253383.27 mm^3
Bulk density of pebbles	3.0184 x 10^{-6} kg/mm^3
Volume of pebbles in pebble bed	157169.36 mm^3
Packing Fraction	0.62028
Heat release per unit length	53.9496 W/m

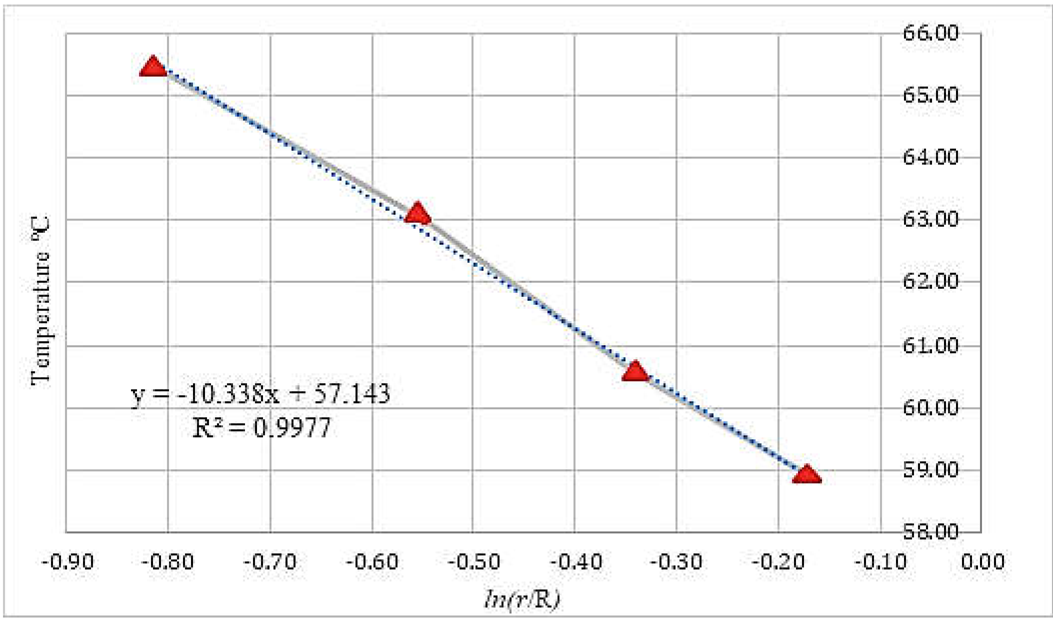

Figure 5. Temperature vs ln (r/R) plot for preliminary run

The measurement of effective thermal conductivity of pebble bed with different mean bed temperature is an important parameter to be evaluated. Li_2TiO_3 pebble bed is investigated for keff at two different mean bed temperatures under helium environment. Helium is filled at absolute pressure of 0.114 MPa for this investigation. Packing fraction of the pebble bed is 62.028%. Total 7 experimental run were taken for this. 4 runs performed without band heaters at room temperature and in 3 runs band heaters were used for elevated temperature of 100 °C. The effective thermal conductivity of Li_2TiO_3 pebble bed plotted with mean bed temperature in Figure 6. The value of keff for Li_2TiO_3 pebble bed made of 1 mm diameter pebbles and 62.028% packing fraction under 0.114 MPa helium pressure. It increased from 0.845 W / (mK) at average bed temperature 71.5 °C to 0.9 W / (m K) at 108.75 °C. This increase clearly shows temperature dependency of the keff. This value is increases with increase in mean bed temperature. Here increase of keff is 6.5% with increase of temperature by 37.26 °C.

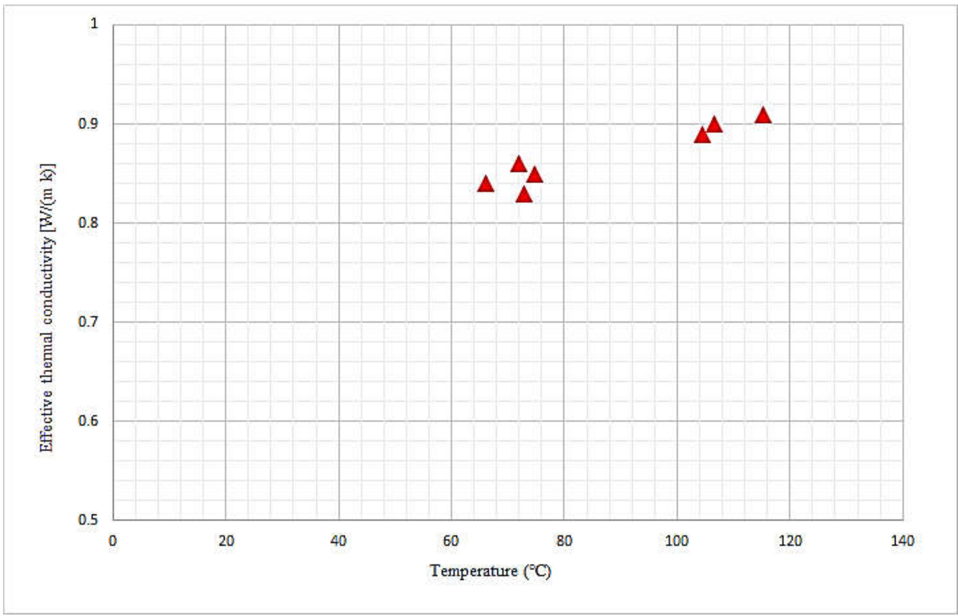

Figure 6. k(eff) vs Tm plot for Li2TiO3 pebble bed

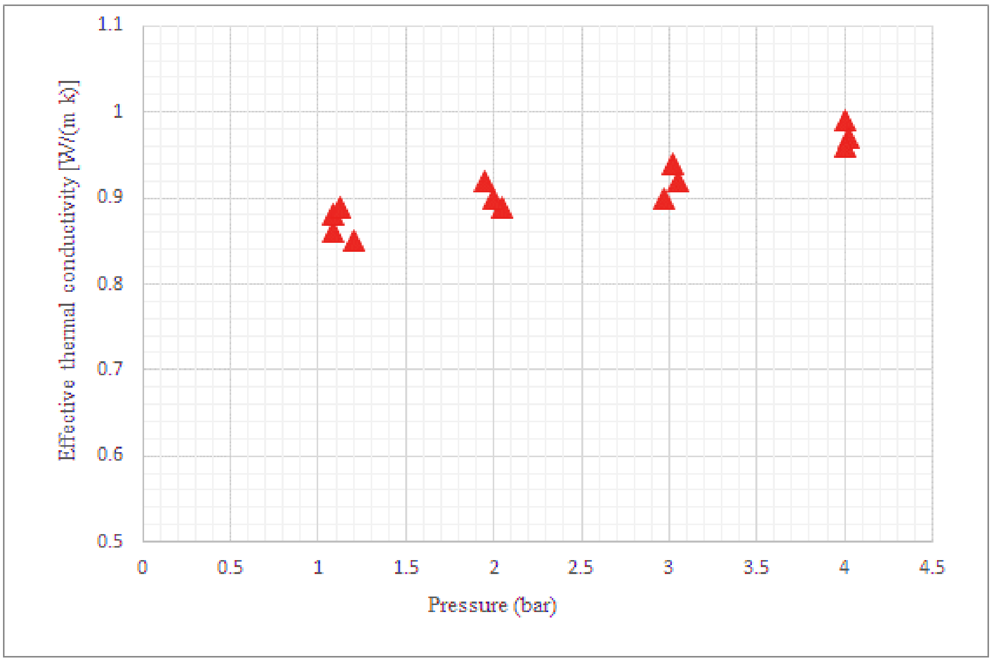

Figure 7. k(eff) vs Helium Pressure plot for Li2TiO3 pebble bed

The measurement of effective thermal conductivity with different helium pressure at RT is important parameter. The value of keff for different helium pressure is investigated with Li_2TiO_3 pebble bed at room temperature. Packing fraction of the pebble bed is 62.028%. results of the investigation is shown in Figure 7. Total 11 readings were taken for this investigation. At 0.1 MPa pressure 4 readings were taken while, at other levels 3 runs were taken. It can conclude that the value of keff for the Li2TiO3 pebble bed is increase with increase of helium gas pressure at room temperature. In this investigation value of keff is increased from 0.87 W / (m K) at 0.12 MPa helium pressure to 0.973 W / (m K) at 0.4 MPa helium pressure. This 11.87% of increase in value shows dependency of the keff with helium pressure at room temperature.

5. SUMMARY AND CONCLUSION

Brief study of fusion and fusion technology was carried out. In the next ITER and plasma was also studied for better understanding and current status of the project. In the literature review, different methods for thermal conductivity measurement were studied in detail. Then after steady-state radial heat transfer method is selected for the development of a new apparatus. Detail study of two distinct test facilities developed based on steady-state radial heat transfer method were studied in detail. One is developed in Germany and another in China. Limitations of those test facilities were identified to avoid in the new facility. Prepared schematic of the full setup. Then, using FEM analysis various parameters of the apparatus are optimized. 3D models of all components were made. The effective thermal conductivity was measured as a function of mean bed temperature in the range of room temperature to 120 `C using 1 ± 0.15 mm diameter Li2TiO3 pebbles. A clear dependence of the effective thermal conductivity on the mean bed temperature of the pebble bed was observed. Experiments were performed in helium atmospheres in the pressure range of 0.05 bar to 3 bar gauge pressure. The effect of pressure variation on the effective thermal conductivity of pebble bed was investigated for the range of 0.05 bar to 3 bar gauge pressure using 1.0 ± 0.15 mm diameter Li2TiO3 pebbles. Effective thermal conductivity of pebble bed was found to be increased with the increase of pressure while using helium as filling gas over a temperature range of room temperature to 120 `C. The effect of pressure change was found to be more significant in the pressure range of 0.05 bar to 1 bar gauge pressure.

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