META:LIC CONCEPT THERMO-HYDRODYNAMICS TESTING FACILITY AT THE INSTITUTE OF PHYSICS OF THE UNIVERSITY OF LATVIA (IPUL)

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Abstract : Heat transfer in the Pb-Bi loop with inductive heat source as a model for proton beam caused heat deposition is considered. The experimental setup for inductive heating does not allow an easy estimation of the deposited total power and its spatial distribution, therefore the total power has been determined indirectly using temperature measurements upstream and downstream of the heated region and flowrate data. The heat source spatial distribution has been determined by axis-symmetric finite element model describing time harmonic magnetic field created by the inductor coil. The calculated temperatures agree well with time averaged thermocouple measurements.

1. Introduction

The aim of the MEgawatt TArget: Lead bIsmuth Cooled (META:LIC) development has been to provide of a comparative target solution to the reference target for ESS [1]. To validate the META:LIC design, experiment focused on thermo-hydrodynamics of the liquid metal flow and was conducted on a mock-up of the META:LIC target at the LBE loop at the Institute of Physics of the University of Latvia (IPUL). The LBE loop has a total length of 10 m and 1100 kg of LBE. The loop is equipped with a cylindrical electromagnetic induction pump with permanent magnets, which is able to provide a liquid metal flow rate up to 12.0 l/s^{-1} at discharge pressure of 4.0 bars. Two flow meters of the induction and conduction types, as well as a Venturi tube are installed on the loop. Pressure is monitored with high temperature pressure transmitter 35 XHTC from KELLER AG.

The heat deposition by proton beam is modelled with inductive heat source. The heating is realized with the aid of a coil (inductor) connected to the high frequency 15 kHz generator. The core of the inductor has been made from the epoxy resin with ferromagnetic particles distributed in the resin, the experimentally determined relative permeability 100. The experimental setup for inductive heating does not allow an easy estimation of the deposited total power and its spatial distribution, therefore the total power has been determined indirectly using temperature measurements upstream and downstream of the heated region and flowrate data. The heat source spatial distribution has been determined by axis-symmetric finite element model describing time harmonic magnetic field created by the inductor coil. Software FEMM [2] is used for electromagnetic problem and ANSYS Fluent [3] for hydrodynamic and heat transfer.

2. Experimental setup

The test section geometry is shown in fig 1. Thermocouples are located at different depth in the melt 2, 4, 6 and 10 mm from the wall. The numbering of thermocouples is shown in fig 2. The thermocouples Tc.t.1-10 are located in close vicinity to the heated zone and, due to the specific character of the heat deposition in the experimental setup, can be used for determination of the temperature distribution. The thermocouples Tc.t.12-14 are located upstream the heated zone and measure the inflowing metal temperature, whereas Tc.t.0 and Tc.t.11 are located downstream the heated zone and are used for the outflowing metal temperature regarding to the heated zone. The measured temperatures by these thermocouples (Tc.t.12-14, Tc.t.0 and Tc.t.11) should be regarded as volume averaged ones due to the turbulent mixing and relatively high distance from the heated zone.

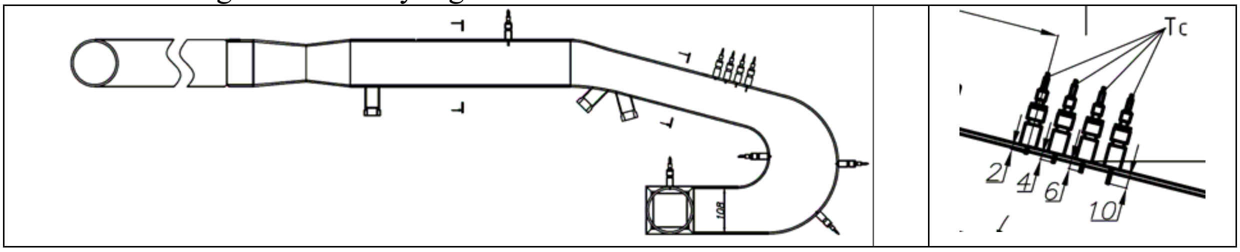

Figure 1: Test section geometry and thermocouple location.

The heat transfer in the loop has been modelled with the inductive heating. The heating is realized with the aid of a coil (inductor) connected to the high frequency (15 kHz) generator, see fig 2. At the chosen frequency the skin depth for stainless steel is about 3,5 mm, therefore the heat source for the melt can be considered as a heat flux at the surface. Temperature measurements with three locations of the inductor have been carried out. They are denoted as left, center and right according to the shown in fig 2 inductor location relative to the thermocouples Tc.t.1-10. The experimental setup for inductive heating did not allow an easy estimation of the deposited total power and its spatial distribution, therefore the total power had to be determined indirectly using temperature measurements upstream and downstream of the heated region and flowrate data.

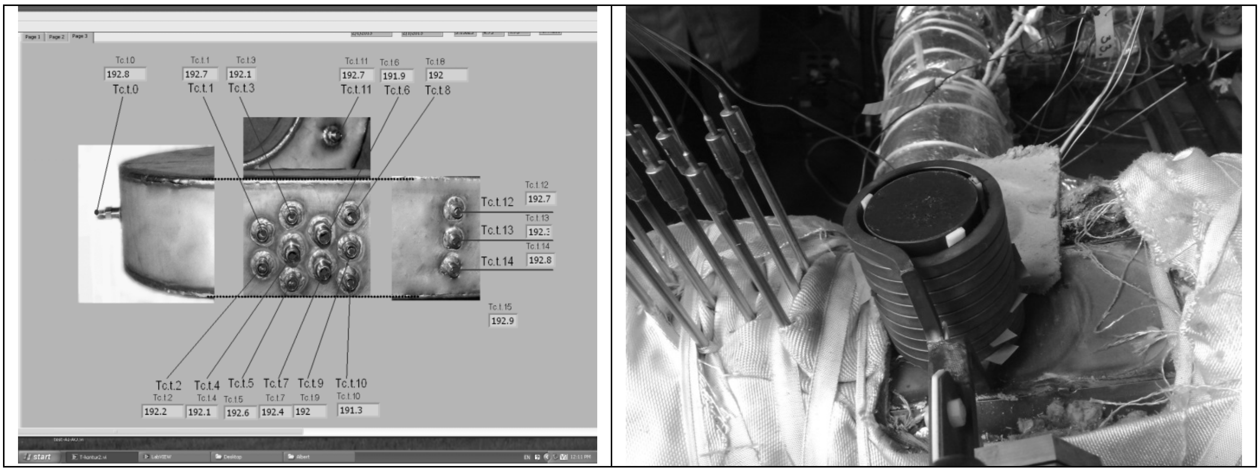

Figure 2: Thermocouple location and numbering and the inductor for heating.

The deposited power has been determined from the integral flow parameters. We use as a characteristic temperature T_{in} for the entrance of heated region and T_{out} for the exit of heated region. The power then is determined as $P = Q\rho c(T_{out} - T_{in})$. The determined values of power for three heater locations (left, center and right - P_l, P_c, P_r and average P_{av}) are presented in table 1. One has to take into account, however, that the measurements are made at specific moments of time and the unsteady character of the flow leads to the temperature fluctuations, decreasing the accuracy of steady state predictions from small number of measurements in time. Nevertheless, this method allows the determination of the total deposited power in the melt even if the accuracy is not very high.

Table 1: Deposited power determined from integral flow parameters

Q(l/s)	P_l (kW)	P_c (kW)	P_r (kW)	P_{av} (kW)
2	6.52	5.63	5.65	5.93
4	9.04	7.23	6.80	7.69
8	7.50	7.68	7.05	7.41

3. Inductive heating model

Another problem is connected with the heat source density distribution over the surface of the channel. The heat source spatial distribution has been determined by axis-symmetric finite element model describing time harmonic magnetic field created by the inductor coil with software FEMM [2]. The parameters used in calculations are presented in table 2.

Table 2: Electrical parameters of the materials

Material	Electrical conductivity (Ms/m)	Relative permeability
316 stainless steel	1.334	1
Pb-Bi	0.9	1
core	0	100

The axis-symmetrical model consisting of core, coil, stainless steel channel wall and lead-bismuth melt with used finite element mesh is shown in fig 3. Due to the high inductor frequency the mesh in channel wall is very fine and the depth of lead-bismuth in the model is limited.

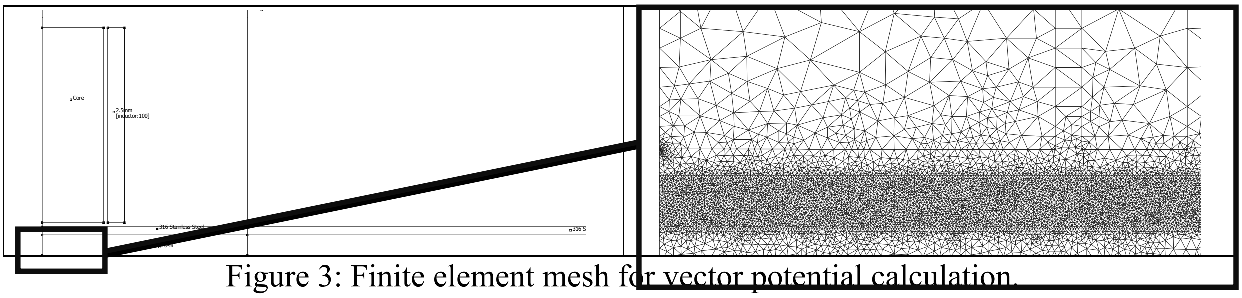

Figure 3: Finite element mesh for vector potential calculation.

The calculated current density and Joule sources are presented in fig 4. As expected, due to the small skin depth, the most of the heat is deposited in channel wall and only small part directly in the liquid metal.

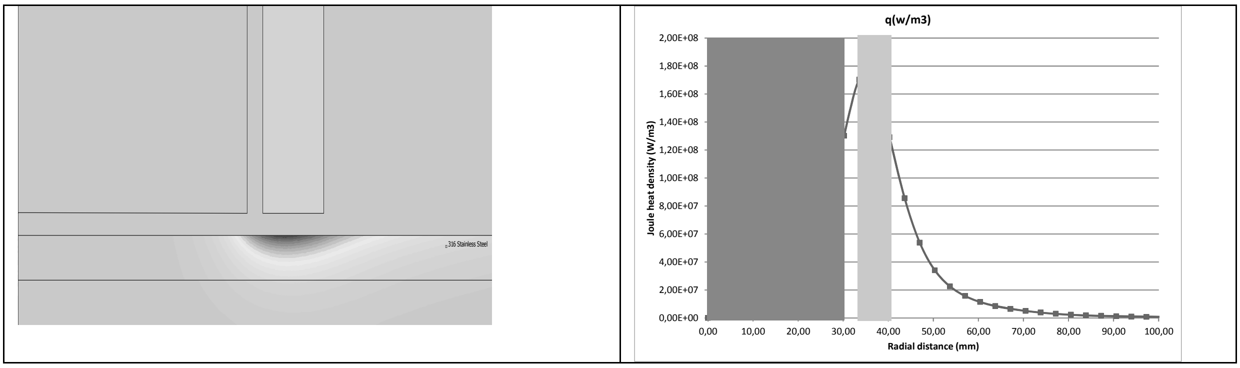

Figure 4: Magnitude of current density (left) and Joule heat source density on the wall surface (right).

This is confirmed by the integral values of the dissipated heat power presented in the table 3. These results indicate, that heat flux boundary condition can be applied to describe the heat source in the considered experimental setup. By decreasing the supply frequency, the skin depth will increase and a volumetric heat source model would be more appropriate.

Table 3: Total dissipated power in stainless steel wall and Pb-Bi

Zone	Power (%)
stainless steel	90.4
Pb-Bi	9.6

As can be seen the heat source density is not homogeneous, the maximum is located under the coil and the minimum is located in the middle of the core. This certainly raises the question on how appropriate is the considered heat source for the modelling proton beam heat deposition, because in the beam the maximum is located in the center. Apparently the proposed method can be used for integral heat transfer model experiments without aiming at precise temperature distributions. At present stage it is assumed that the power is located in the outer half of the radius of the circular surface with diameter 80 mm.

4. Heat transfer model

The heat transfer has been calculated with Ansys Fluent 12. k- ω SST model of turbulence. Pb-Bi properties are taken from [4]. The comparison of measured and calculated values of the temperature at the thermocouple Tc.t8-10. locations (table 4) shows good agreement. Despite symmetrical inductor and thermocouple arrangement, the measured temperature distribution is not symmetrical to the channel middle plane. The downstream geometry has impact on the flow distribution in the heat transfer zone, therefore the results are limited to the specific geometry in the considered experimental setup. The present study has been focusing on the channel part downstream the heated zone, but certain influence is also expected from the upstream geometry.

Table 4: Calculated and measured temperatures

Thermocouple location	Calculated velocity (m/s)	Calculated temperature (°C)	Measured temperature (°C)
Tc.t8	0.85	205.5	201.9
Tc.t9	0.91	197.7	198.4
Tc.t10	0.90	199.9	199.9

3. Conclusion

- The inductive heating can successfully be used for the modeling of the integral heat deposition in the spallation target. The local heat and temperature distributions are different.
- By adjusting the frequency it is possible to achieve different depth of heat deposition.
- Reliable determination of the total power might require some additional measurements of the temperature upstream and downstream the heated zone.
- Heat source density distribution over the surface has to be determined separately experimentally or by solution of corresponding eddy current problem.
- The unsteady character of the flow leads to the temperature fluctuations, decreasing the accuracy of steady state predictions from the measurements.
- The results are limited to the specific geometry in the considered experimental setup. The loop geometry influences the flow conditions in the heat transfer zone, investigated case shows the downstream geometry influence, upstream geometry also might have influence on the flow and, consequently, heat transfer conditions in the heat deposit zone.

4. Acknowledgements.

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5. References

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