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Natural circulation in a liquid metal one-dimensional loop

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ABSTRACT

A wide use of pure lead, as well as its alloys (such as lead–bismuth, lead–lithium), is foreseen in several nuclear-related fields: it is studied as coolant in critical and sub-critical nuclear reactors, as spallation target for neutron generation in several applications and for tritium generation in fusion systems. In this framework, a new facility named NAtural CIrculation Experiment (NACIE), has been designed at ENEA-Brasimone Research Centre. NACIE is a rectangular loop, made by stainless steel pipes. It consists mainly of a cold and hot leg and an expansion tank installed on the top of the loop. A fuel bundle simulator, made by three electrical heaters placed in a triangular lattice, is located in the lower part of the cold leg, while a tube in tube heat exchanger is installed in the upper part of the hot leg. The adopted secondary fluid is THT oil, while the foreseen primary fluid for the tests is lead–bismuth in eutectic composition (LBE). The aim of the facility is to carry out experimental tests of natural circulation and collect data on the heat transfer coefficient (HTC) for heavy liquid metal flowing through rod bundles. The paper is focused on the preliminary estimation of the LBE flow rate along the loop. An analytical methodology has been applied, solving the continuity, momentum and energy transport equations under appropriate hypothesis. Moreover numerical simulations have been performed. The FLUENT 6.2 CFD code has been utilized for the numerical simulations. The main results carried out from the pre-tests simulations are illustrated in the paper, and a comparison with the theoretical estimations is done.

1. Introduction

A wide use of pure lead, as well as its alloys (such as lead–bismuth), is foreseen in several nuclear-related fields: it is studied as coolant in critical and sub-critical nuclear reactors, as spallation target for neutron generation in several applications and for tritium generation in fusion systems.

For the design of innovative HLM components Computational Fluid Dynamics (CFD) codes are considered an essential tool [1–3]. Therefore, experimental activities and numerical simulation campaigns have been carried out in strong correlation in order both to understand the capabilities of these computational codes to correctly predict the characteristics of HLM turbulent flows and to improve their performances. A fundamental contribution has been imparted by the important progress in measurement techniques achieved in the past decade, enabling a first access to these complex flow phenomena.

The development process going on permits to develop always more realistic models for the heat transfer, the MHD flows and the free surface problems and also to generate a database and to find the correlations needed to design innovative systems.

In this framework, a new facility named NAtural CIrculation Experiment (NACIE), has been designed at ENEA-Brasimone Research Centre. NACIE is a small LBE loop designed to study the natural circulation regime in support of ICE (Integral Circulation Experiments) activities, in the framework of the FP6 project EUROTRANS-DEMETRA which are aimed to verify the coupling, in a significant scale, of a heat source with a cold sink in a pool configuration representative of the geometry of the European Transmuter Demonstrator (ETD) reactors under development. The main objectives of NACIE are to obtain data on the natural circulation heat transfer coefficient in rod bundle assemblies.

In this framework, preliminary numerical simulations in support of the design have been carried out and the obtained results have been compared with the theoretical estimation. The FLUENT 6.2 CFD code has been utilized.

2. The NACIE loop

NACIE is a lead bismuth eutectics (LBE) loop which basically consists of two vertical pipes (O.D. 2.5 in.) which work as riser and downcomer, connected by means of two horizontal branches (O.D. 2.5 in.). In the bottom part of the riser a heat source of about 30 kW is installed, while the upper part of the downcomer is connected to an heat exchanger. The difference in level between the barycentre of the heat source and the one of the cold sink has been

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fixed to reproduce the same gap that characterises the ICE test section (H = 4.5 m).

The possibility to house drilled disks with calibrated holes of different sizes, by means of two flanges installed in the cold part of the loop, will allow to change the concentrate loss of pressure of the system.

The loop is completed by an expansion vessel, installed on the top part of the loop, coaxially to the riser. The general lay-out of the loop is depicted in Fig. 1.

The main components of the loop are synthetically described in the following.

2.1. Heat source

The heat source will be arranged to simulate hydraulic conditions as close as to what is expected for the ICE heat source. To obtain this, three electrical cartridges will be assembled in a triangular lattice, according to the following parameters:

- active length of the pin (L_{att}): 1000 mm;
- pitch-diameter ratio (p/D_{est}): 1.4;
- overall power (P_{th}): 30 kW
- external diameter: D_{ext} = 19.05 mm;
- wall heat flux: q^* = 15.6 W/cm^2.

A pitch-diameter ratio of 1.4 allows to consider the pins thermically independent one from each other [4,5].

The average velocity in the channel is expected to be in the range 0.2–0.5 m/s. The reference clad material for the cartridges is AISI 316 L steel.

2.2. Expansion Vessel

The expansion vessel is connected to the upper part of the riser. It provides a suitable volume to allow the LBE expansions during the thermal transients necessary to reach the average test temperature. The free level of the LBE will be maintained under an Argon atmosphere, with a slight overpressure (100 mbar).

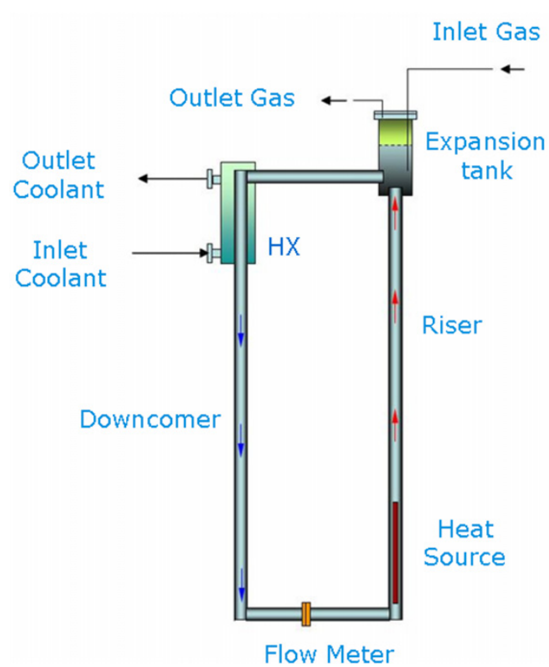

Fig. 1. General lay-out of the NACIE loop.

2.3. Heat exchanger

The heat exchanger designed for the NACIE loop is a '*tube in tube*', counter flow type; the reference choice for the secondary fluid is the DIPHYL THT OIL.

3. The analytical model

In order to calculate the LBE flow rate through the NACIE loop, the momentum equation for the steady state conditions gives the following result:

$$\Delta p_{DF} = \Delta p_{frict}, \tag{1}$$

where the term Δp_{DF} indicates the driving force for the natural circulation, while Δp_{frict} refers to the total pressure drops along the loop.

The driving force term, which involves the buoyancy force, is due to the liquid metal density variation along the heat source, and it is expressed as below

$$\Delta p_{DF} = \Delta \rho g H, \tag{2}$$

where H indicates the effective elevation change between heating and cooling centres.

The thermal barycentre can be considered coincident with the geometric one if the heat flux along the axis is uniform. This hypothesis is acceptable for both the heat source and the HX because in the first case the heat flux in the fuel rod is axially uniform, while the reference solution for the HX is a tube in tube counter-current type.

$\Delta\rho$ is the variation of density that the liquid metal undergoes from the inlet to the outlet section of the heat source. In order to evaluate this term, the Boussinesq approximation has been adopted [6]

$$\rho(T) = \rho_0[1 - \beta_0(T - T_0)], \tag{3}$$

where β is the fluid isobaric thermal expansion coefficient, defined as follows:

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p. \tag{4}$$

By Eqs. (3) and (4), the $\Delta\rho$ term is calculated; the subscript '0' indicates the average condition in the loop.

$$\Delta\rho = \rho_{in} - \rho_{out} = \rho_0\beta_0(T_{out} - T_{in}) = \rho_0\beta_0\Delta T. \tag{5}$$

In the end, the driving force term can be written as function of the thermal power and the loop flow rate.

$$\Delta p_{DF} = gH\rho_0\beta_0\Delta T = gH\rho_0\beta_0\frac{P_{th}}{\dot{M}c_{p0}}. \tag{6}$$

To evaluate the total pressure drop along the flow path, a total singular pressure drop coefficient K is defined [6]:

$$K(\dot{M}) = \sum_N \left[\left(k + f\frac{L}{D_H}\right)_i \frac{A_{eff}^2}{A_i^2}\right], \tag{7}$$

where

- k is the singular pressure drop coefficient in the ith branch of the loop [6];
- f is the Darcy–Weisbach friction factor in the ith branch of the loop [6];
- L, D_H, A_i are the length, hydraulic diameter and flow area of the ith branch of the loop;
- A_{eff} is the main cross section along the flow path.

In the general case, the $K(\dot{M})$ coefficient is a function of the mass flow rate. If the singular pressure drop along the flow path is much greater than the distributed one, it is possible to assume that this coefficient is independent from the LBE flow rate [6].

The NACIE loop has been designed in accordance with this assumption

$$K(\dot{M}) = \text{cost}. \tag{8}$$

In fact, in order to simulate different pressure drop conditions, it will be possible to place different drilled disks in the flow path, which are characterized by high values of k. In any case, for the configuration adopted for the expansion tank installed in the plant a high value of the singular pressure drop is introduced in the loop.

The friction term of Eq. (1) is expressed as follows:

$$\Delta p_{\text{frict}} = K\frac{1}{2}\rho_0 w_{\text{eff}}^2 = K\frac{1}{2}\frac{\dot{M}^2}{\rho_0 A_{\text{eff}}^2}, \tag{9}$$

where ρ_0 indicates the LBE density corresponding to the average temperature in the loop. Being NACIE mainly a uniform cross section loop (apart from the heat source), the A_{eff} is coincident with the cross section of the pipe.

By Eqs. (6) and (9), the momentum balance, along the loop, is expressed as follows:

$$K\frac{1}{2}\frac{\dot{M}^2}{\rho_0 A_{\text{eff}}^2} = gH\rho_0\beta_0\frac{P_{\text{th}}}{\dot{M}c_{p0}}. \tag{10}$$

Reordering Eq. (10), it is possible to determine the mass flow rate in the natural circulation flow regime

$$\dot{M} = \left(2\frac{\rho_0^2\beta_0}{c_{p0}}gA_{\text{eff}}^2\frac{P_{\text{th}}}{K}H\right)^{\frac{1}{3}}. \tag{11}$$

Fig. 2 shows the trend of the primary flow rate as function of the average system temperature and for different values of the total singular pressure drop coefficient.

After that the LBE flow rate has been calculated, it is possible to evaluate the thermal jump between the inlet and outlet heating section (HS) using the following equation:

$$T_{\text{out}} - T_{\text{in}} = \Delta T = \frac{P_{\text{th}}}{\dot{M}c_{p0}}. \tag{12}$$

The flow area in the HS, A_{HS}, can be calculated as follows:

$$A_{\text{HS}} = A_{\text{eff}} - N_r A_r, \tag{13}$$

where N_r indicates the number of heater rods in the bundle, each one with a section of A_r.

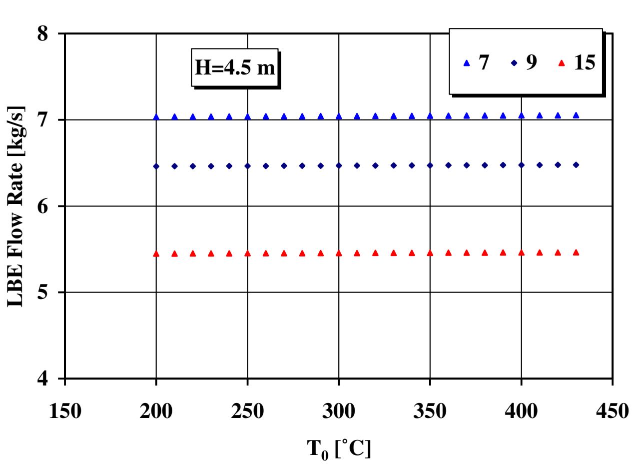

Fig. 2. LBE Flow Rate in the NACIE loop.

Table 1
Re number and loop average velocity inside the HS (T_0 = 300 °C)

K (–)	Re (–)	w_{HS} (m/s)
7	7.7×10^4	0.22
9	7.1×10^4	0.20
15	6.0×10^4	0.17

The average velocity inside the HS is

$$w_{\text{HS}} = \frac{\dot{M}}{\rho_0 A_{\text{HS}}}. \tag{14}$$

In Table 1, the Reynolds number (Re) and average velocity (w_{HS}) inside the HS carried out by the analytical calculations, are listed for different values of the total singular pressure drop coefficient; all the values are reported for a loop average temperature of 300 °C.

4. The numerical simulations

4.1. The CFD model

The main idea of the CFD simulations is to carry out some preliminary evaluations in support to the design of NACIE.

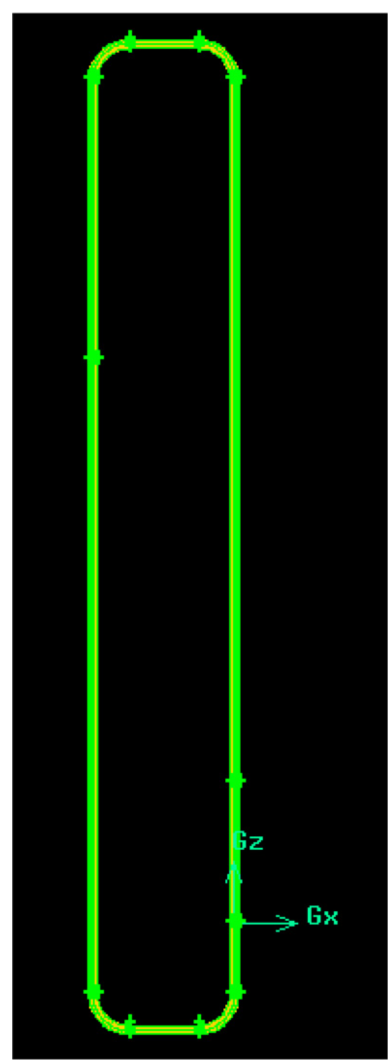

Fig. 3. Sketch of the adopted domain.

In this framework, the campaign consists of in a series of simulations with the objective to determine the LBE flow rate along the loop.

In order to optimize the numerical calculations (reducing the CPU time), some hypotheses have been adopted to obtain the model of the loop. The expansion tank has not been simulated along the loop, reducing strongly the cell number needs to simulate the loop.

Exploiting the NACIE symmetry, only half of the loop has been simulated, cutting it with a vertical plane (see Fig. 3).

The spatial domain has been divided in 10 volumes, to optimize the mesh process.

The heating volume consists of the fluid pipe volume plus the solid pin volumes (see Fig. 4); a surface source on the pin walls has been adopted.

An appropriate mesh has been realized for these volumes, as shown in Fig. 4, structured in the vertical direction with a pitch of 1 cm, as can be noticed from Fig. 5.

For each wall a boundary layer has been created, to improve the performance of the mesh.

For the discretization of the overall domain, 262 816 cells have been adopted.

A segregated implicit approach has been chosen. A steady state analysis has been performed.

Regarding the discretization of the governing equations, a first order upwind scheme has been adopted for momentum, turbulence kinetic energy, turbulence dissipation rate and energy equations, while a body force weighted scheme has been used for interpolating the pressure values.

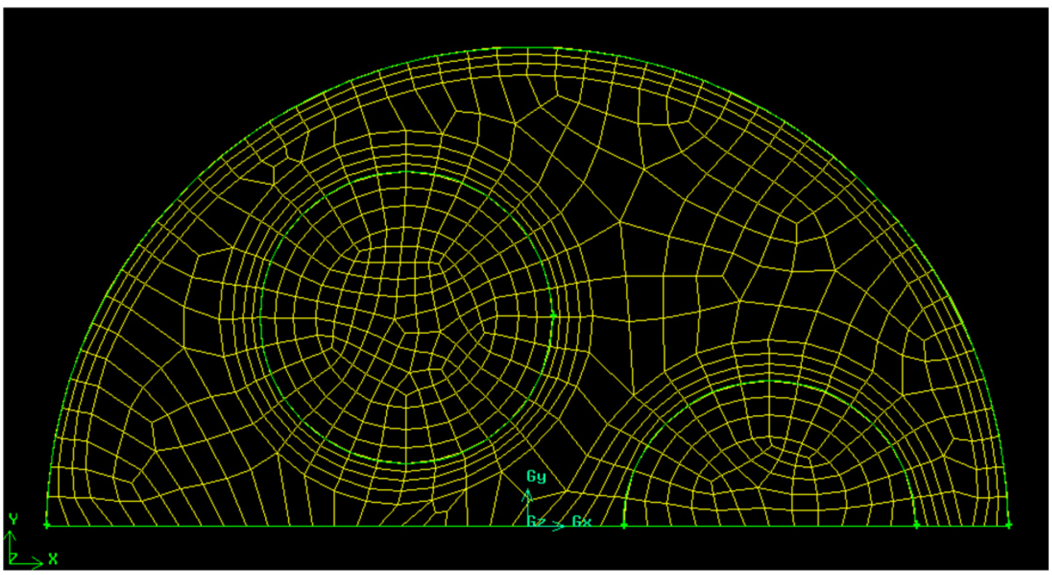

Fig. 4. Mesh adopted in the heating section.

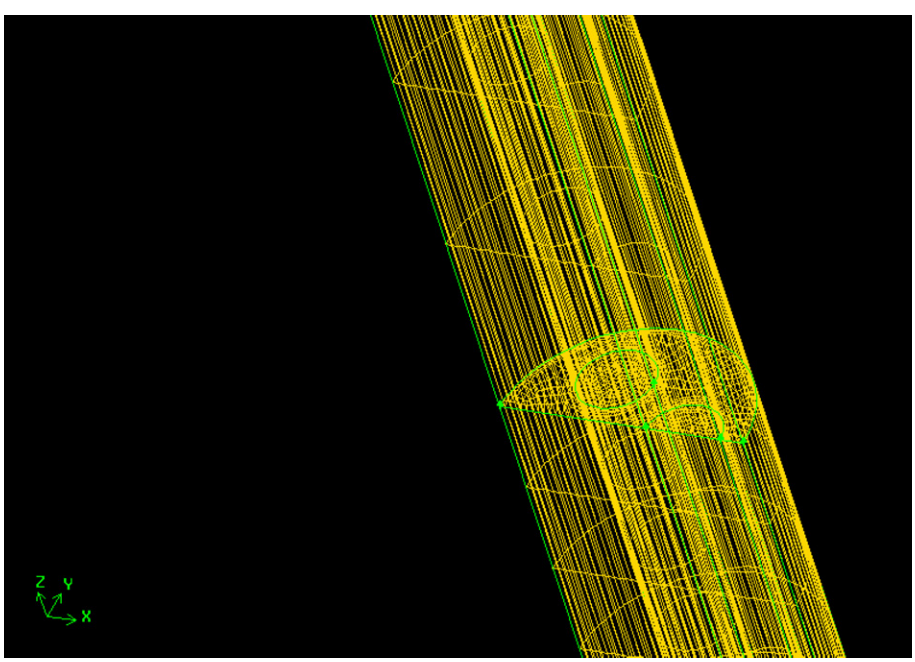

Fig. 5. Vertical mesh (structured).

The adopted model for the simulation of the turbulence is RNG k–ε model, with standard wall treatment [7].

The RNG k–ε model was derived using rigorous statistical technique (Renormalization Group Theory); it is similar in form to the standard k–ε model, but includes some refinements.

In particular, the RNG theory provides an analytical formula for turbulent Prandtl number (Pr_t) (instead of a constant value as in the standard k–ε model), to take in account the experimental evidence indicating that the Pr_t varies with the molecular Prandtl number and turbulence; in fact it is know that an accurate expression of the Pr_t is very important in simulating turbulent heat transfer in liquid metal flow[1–4], [7].

Moreover, the RNG and standard k–ε model are isotropic models [1–3], so they could not reproduce the secondary flow which occurs in the flow channel with non circular cross section [2]; for this aim second order closure turbulence models should be adopted, i.e. Reynolds Stress Model of Speziale (SSG model) [2].

Finally, because the aim of this work is to get a preliminary overview of the fluid dynamics behaviour of the NACIE loop, the RNG model has been chosen because its robustness and wide spread use, even if it is well know that it deficits for low molecular *Pr* number flows simulations [1–4].

To simulate the turbulent flow regime and heat transfer in the NACIE heating section and heat exchanger, more accurate simulations have to be performed, paying more attention for the mesh process, adopted turbulence model and turbulent Prandtl number evaluation.

To perform the simulations, two materials have been defined; the main properties are listed in the Table 2 [8] and Table 3 [7].

On the pin walls a heat flux of 167780.9 W/m^2 has been imposed. Regarding the heat exchanger, its secondary side was not simulated; to take in account the heat sink a cooled surface has been simulated on the HX boundary wall, imposing a heat transfer coefficient of 2134 W/m^2 K; a value of 5.2 mm has been adopted as wall thickness and a free stream temperature of 493.15 K has been utilized on the oil side.

The heat transfer coefficient oil side has been evaluated adopting the Dittus–Boelter correlation [6].

As convergence criterion, a decrease in the scaled residuals to 10^{-7} has been fixed, except for the energy, where a value of 10^{-9} has been considered.

Table 2
Thermal physical properties adopted for the LBE [8]

Material	LBE
ρ (kg/m^3)	$11\,096 - 1.3236 \cdot T$
C_p (J/kg K)	$159 - 0.0272 \cdot T + 0.00000712 \cdot T^2$
k (w/m K)	$3.61 + 0.01517 \cdot T - 0.000001741 \cdot T^2$
μ (Pa s)	$0.000494 \cdot \exp(754.1/T)$

Table 3
Thermal physical properties adopted for the steel [7]

Material	Steel
ρ (kg/m^3)	8030
C_p (J/kg K)	502.48
k (w/m K)	16.27

A sensitivity analysis on the mesh has been performed, changing the number of volumes (90 000–300 000) and the discretization schemes adopted on each section. The one here described (about 260 000 volumes) supplied the best performances in terms of CPU time and solution independence from the number of utilized cells.

4.2. Main results

The results carried out by the numerical simulation are in good agreement with the preliminary analytical evaluation.

In Fig. 6 the contours of the velocity in the outlet section (hottest section) of the NACIE heater are plotted.

The LBE flow rate computed by the FLUENT code is 6.98 kg/s, while the analytical foreseen value is 7 kg/s (assuming $K = 7.2$, estimated neglecting the expansion vessel pressure loss contribution).

In Fig. 7 the contours of the temperature in the outlet section (hottest section) of the NACIE heater are plotted.

The ΔT between the inlet and the outlet sections of the heater is 29.6 K evaluated by the code, while the one calculated analytically is 29.9 K.

About the adopted discretization, the performed mesh shows a wall y-plus values in accordance with the values foreseen by the theory for the turbulence model (ref. value: 30–300).

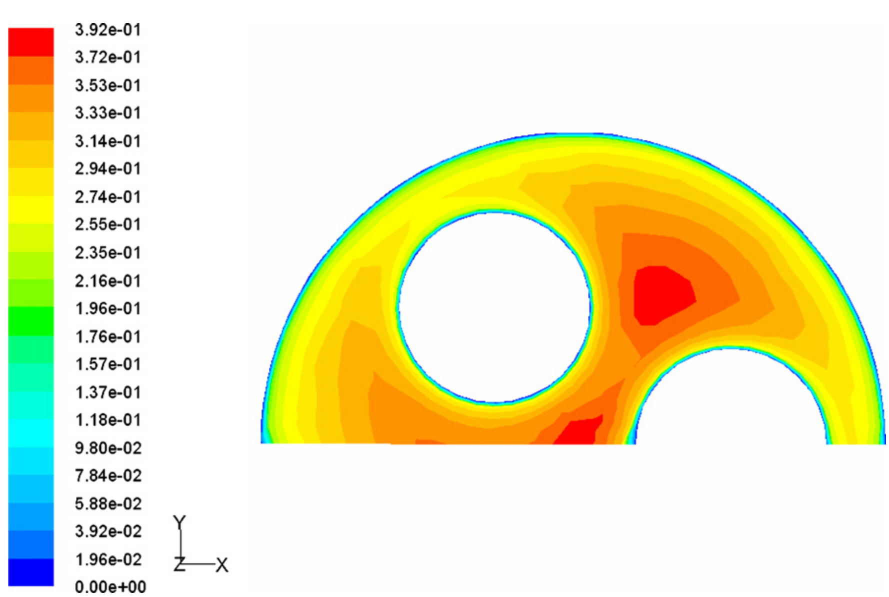

Fig. 6. Velocity contours in the outlet section of the NACIE heater (m/s).

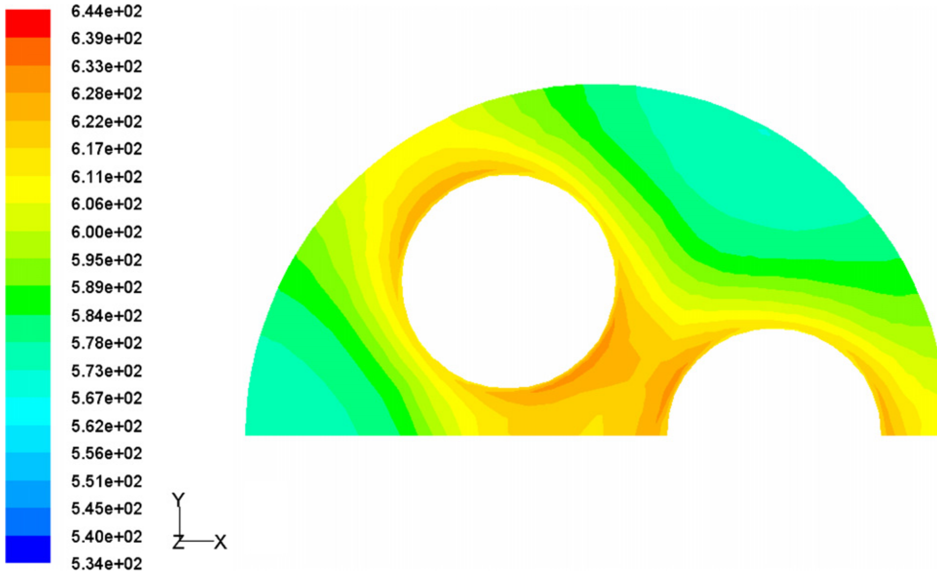

Fig. 7. Temperature contours in the outlet section of the NACIE heater (K).

5. Conclusions

The numerical simulations performed are preliminary ones, to obtain some useful indications for the design of the NACIE facility. Both the numerical and the analytical models should be improved evaluating the contribution to the primary circulation of the expansion vessel. A set of suitable numerical simulations to evaluate the pressure losses inside the expansion vessel could be useful to refine the analytic model. In fact, being that is not possible to determine the pressure losses along the expansion vessel analytically, the CFD simulations could be used to complete the analytical description itself.

Moreover, to accomplish the design of the loop, several numerical simulations have to be performed with the aim to evaluate the heat transfer coefficient inside the heating section and heat exchanger; to simulate the turbulent flow regime and heat transfer, more accurate simulations have to be carried out, analyzing and optimizing the mesh process, the choose of the turbulence model (isotropic, anisotropic) and the turbulent Prandtl number evaluation.

Acknowledgement

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