One dimensional modelling of flow in a helium loop

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Abstract. The natural circulation helium loop is a facility designed for decay heat removal from ALLEGRO fast nuclear reactors. The article deals with the observation of pressure and velocity relations during steady flow of helium. A one-dimensional numerical model of flow capable of determining the velocity with sufficient accuracy is presented in the article. The model describes the flow of highly compressed gaseous medium with variable density in direct pipelines with local resistances. It's a hydraulic model, which means that the temperature distribution along the loop must be known. The article also includes the evaluation of local resistances in DHR and GFR, which significantly affects the resulting accuracy. The results from numerical model are compared with experiments.

1 Introduction

After the Fukushima nuclear disaster on 11. Mach 2011, the role of passive safety of nuclear power plants has increased considerably. The new main objective is to minimize the dependence on electrical supply. In the age of carbon dioxide emission regulations, the nuclear energy is an alternative to green energy sources, which puts passive safety systems on the path of sustainable development. New generation of nuclear power plants are being developed, which are based on the success of the use of nuclear power and the experience from operating facilities. Some new reactor solutions rely on passive systems that can meet safety requirements. In recent years, passive security systems have proven to be elements that can make a significant contribution to simplifying and potentially improving the economy of new nuclear power plants. The use of passive safety systems eliminates the costs associated with installation, maintenance and operation of active safety systems that require multiple pumps with independent and redundant power supplies. Consequently, passive safety systems are considered in new reactor concepts particularly in the IV. generation reactor designs [1]. Another incentive to use passive security systems is the potential for increased security through increased system reliability, because passive systems don't have any moving parts which could fail during operation. Another safety factor is the used medium, helium. Because of suitable chemical and physical properties helium can't get radioactive at used conditions and can't interact with other substances as

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it's chemically inert. It is non-toxic and has high values of thermal conductivity and specific heat.

2 Experimental facility

Helium loop should serve as a safety system for decay heat removal from nuclear reactors of IV. generation. Helium is supposed to be heated directly from the nuclear reactor and then to be cooled down in the heat exchanger (water). The flow of helium should be ensured only by the difference of densities in hot and cold piping branch. The power to drive is thus obtained directly from the heat supplied [2]. It is a vertical heater-horizontal cooler type, single-phase, closed loop. The experimental helium loop facility was built as a model of real helium loop supposed to be used in nuclear power plants and its purpose is the research of helium flow characteristics at various conditions. It is located in the area of Energomont s.r.o. in Trnava. It consists of two main elements, the GFR (reactor substitution) and the DHR (heat sink), along with two piping branches (hot and cold). The GFR is a heater with maximum installed power of 500 kW of which the adjustable power range is 220 kW. The projected heat output of the DHR is also 220 kW with possible water flow regulation. Pressure, pressure difference on the elements, helium temperatures, surface temperatures, water flow, inlet power and velocities are measured during the experiment at several points along the loop. Measurement of helium velocity is performed using a Pitot probe. The compressibility of helium can be neglected along the loop due to relatively small changes in pressure (maximum hundreds of pascals). Helium can achieve the following operating values based on the settings of GFR and DHR devices:

- Helium temperature at the inlet to GFR: 400 ºC – 520 ºC
- Helium temperature at the outlet from GFR: 150 ºC – 250 ºC
- Operating pressure: 3 MPa – 7 MPa

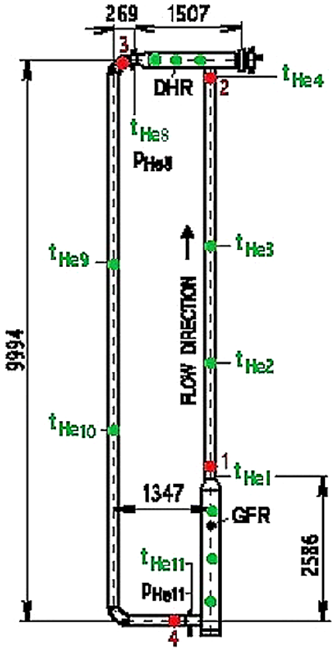

Fig. 1. Diagram of experimental helium loop built within the Allegro project.

The experimental facility provides an opportunity to verify and research the thermodynamic and hydraulic properties of a self-driven, highly compressed, helium flow. The facility enables modelling of changes in input and output power of elements, as well as changes in operating pressure. It is used for the research of steady and unsteady helium flow in a given range of pressures and temperatures [4].

Figure 1 represents the diagram of the experimental facility. Besides the geometry it also shows the positions of measuring elements for temperature, pressure and velocity. The facility encompasses an advanced system of automatized data collecting and evaluating. As the heat conduction through pipes to the surroundings is generally neglected, the most important values from the measurement are temperatures and velocities from the control points 1-4, which are marked with red colour. The measured temperature distribution along the loop is required as an input to the numerical model along with the operating pressure.

The experimental facility further allows: vacuuming of the primary circuit before it is filled with the test medium (He), controlling the primary circuit pressure in the range of 3 MPa to 7 MPa by releasing the test medium into the low-pressure reservoir, refilling the medium back into the high-pressure reservoir, continuous refilling of the test medium to the circuit from an external source in case of leakage of the test medium [4].

3 Hydraulic model of flow

The authors of this article describe a method based on previous works [2], [3]. The basis is that the flow depends on the difference of densities in the cold and hot branch. For a closed loop we can write the balance:

$$\left(\rho_{CB} - \rho_{HB}\right) gh = \sum_{i=1}^{n} p_{li} \tag{1}$$

Where the left side of the equation represents the potential energy available due to different densities in the cold (ρ_{CB}) and the hot (ρ_{HB}) branch. During steady flow, the equation must be valid as the flow can not continuously accelerate or slow down, so the potential energy gained must be spent on the pressure losses p_l. The sum of pressure change across the loop (i.e., 1-2-3-4-1) must be zero (steady flow):

$$\sum_{i=1}^{3}\left(p_i - p_{i+1}\right) + \left(p_4 - p_1\right) = 0 \tag{2}$$

The method uses a relation for calculation of pressure change between two points during steady flow [3].

$$p_{j+1} = \sqrt{\frac{p_j^2}{e^{\alpha}} - \lambda \frac{L}{d} \frac{zRT_{mean}}{A^2} Q_m^2 \left(\frac{e^{\alpha} - 1}{\alpha\, e^{\alpha}}\right)} \tag{3}$$

$$\alpha = \frac{2g\left(h_{j+1} - h_j\right)}{zRT} \tag{4}$$

where p_j – pressure at the inlet to pipe; h_j, h_{j+1} – height at the inlet and outlet of pipe, respectively; Q_m – mass flow, z – compressibility factor; v – mean velocity; A – cross-sectional surface. As temperatures must be known, this method serves in particular, to observe the effect of pressure loss on the mass flow during the operation. The equation contains two unknowns that are dependent on each other, namely the mass flow Q_m and the pressure at the next point p_{i+1}. Thus, the calculation was possible only with iterative method [3].

We calculate the pressure p_{i+1} with equation (3) from the pressure at the previous point. This way, we can gradually calculate the pressure at each control point on the loop and return to the starting point 1. As the initial pressure, we choose the total operating pressure - $p_{1,est}$ which is either chosen as the condition at which we want to calculate the velocity or in our case, this is the measured pressure at point 1. Then, the calculated pressure $p_{1,calc}$ can be obtained as follows:

$$p_{1,est} \xrightarrow{Hot\ Branch} p_2 \xrightarrow{DHR} p_3 \xrightarrow{Cold\ Branch} p_4 \xrightarrow{GFR} p_{1,calc} \quad (5)$$

When calculating the pressure at points 2, 3, 4, 1, the relationship (3) is always used. At places where the local losses are significant (GFR and DHR) the friction factor λ is expressed in terms of local losses coefficient ξ as described in section 3.2 equation (12). During steady flow, the pressure difference must be zero, so we can write

$$f\left(Q_m\right) = p_{1,calc} - p_{1,est} = 0 \quad (6)$$

Due to this condition, which must be kept, we can iteratively calculate the mass flow as well as the flow velocity from measured temperatures and operating pressure. The mean temperature T_{mean} that is in equation (3) is determined from the measurement as the average between two points. The calculation is performed by the iterative Newton method (7), which serves to find the root of the equation (6). The new mass flow rate after each iteration is determined as:

$$Q_m^{j+1} = Q_m^j - \frac{f(Q_m)}{f'(Q_m)} \quad (7)$$

For the first iteration, the initial value of the mass flow is chosen in the order close to predicted value. The derivation of the function is calculated by numerical derivation:

$$f'(Q_m) = \frac{f(Q_{m,h}) - f(Q_m)}{h} \quad (8)$$

The member $f(Q_{m,h})$ expresses the difference between the selected pressure $p_{1,est}$ and the pressure $p_{1,h}$. This pressure ($p_{1,h}$) is calculated analogously to $p_{1,calc}$ with increased mass flow by differential value: $Q_{m,h}^j = Q_m^j + h$ where $h = 10^{-5}$.

$$f(Q_{m,h}) = p_{1,h} - p_{1,est} \quad (9)$$

The stop condition is set to $Q_m^{j+1} - Q_m^j < \varepsilon$, where $\varepsilon = 10^{-5}$. When this condition is reached, the iteration cycle ends and the velocity at any point on the loop is calculated from the continuity equation:

$$v_i = \frac{Q_m}{\rho_i A_i} \quad (10)$$

3.1 Pressure losses due to friction

In order to calculate the losses due to friction a method available from the literature was used. The equation for calculation of friction factor, also known as the McKeon relation was used in the form:

$$\frac{1}{\sqrt{\lambda}} = 1.930\log\left(\mathrm{Re}\sqrt{\lambda}\right) - 0.537 \tag{11}$$

The equation (11) is a regression of measured data and is considered as one of the most accurate. The McKeon relation can be used only for smooth pipes and the literature [6] states the maximum error of 1.25 % for low Reynolds values in range of 0 < Re > 310.10^3, and error of 0.5 % for range 310.10^3 < Re > 18.10^6. In our case, the Reynolds numbers are approximately in the range of 15.000 to 37.000 unless we count the start-up.

3.2 Local pressure losses

The biggest hydraulic loss in the loop occurs in the heater (GFR) and in the cooler (DHR). These losses are introduced into equation (3) by calculating the friction factor related to local loss coefficient.

$$\lambda = \xi_{DHR/GFR} \frac{L}{d} \tag{12}$$

Equation (12) needs the local loss coefficient as input, which had to be calculated separately for both elements by adjusting the well-known equation for pressure losses due to local resistance [2]:

$$\sqrt{p_l} = \sqrt{\xi}\left(\frac{\sqrt{\rho_{ie}}}{2} v_{ie}\right) \tag{13}$$

As the flow in GFR and DHR can't be considered as isothermal, the density and the mean velocity change from the input to the output in both elements. Thus, the local loss coefficient ξ was related to the averaged values of the changing parameters v_{ie} and ρ_{ie} [2]. The pressure loss inside the elements was calculated by the Bell-Delaware method for each measurement, which is considered to be sufficiently accurate. Subsequently, losses from sudden expansion and reduction at inputs and outputs were added. Function (13) is a straight line with $\sqrt{\xi}$ being its slope. By plotting the dependence into a graph and after data regression, it was possible to determine the local loss coefficients ξ_{DHR} and ξ_{GFR}.

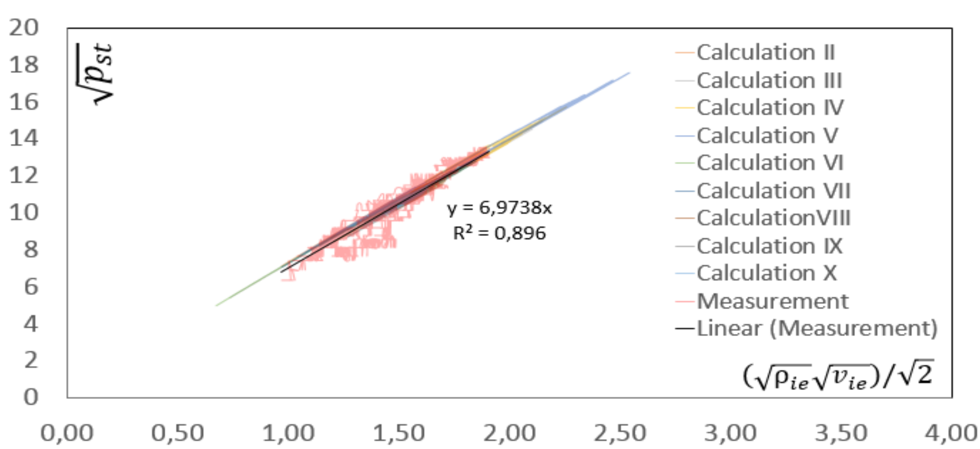

Fig. 2. Determination of local loss coefficient for DHR.

Figure 2 shows nine plotted dependencies in which the pressure loss was calculated by the Bell-Delaware method and one dependency with directly measured pressure loss. The measurement is consistent with calculations. The final value of ξ_{DHR} was thereby determined at: 48.837 and the value for ξ_{GFR} at: 4.875.

4 Comparison of experiments with calculations

The measurement begins with the helium being filled into the system at pressure 2.5 MPa. After the heat input increases, the temperature in the hot branch rises and a flow is induced. By consequent helium cooling in the DHR exchanger, the temperature difference between two branches stays constant at the steady state. In Figure 4, the measured velocities v_H are compared with those calculated using the model described in section 3. The temperature distribution, as well as operating pressure, is a necessary input to the calculation and was obtained from the measurement. The state properties of helium required for the calculation were obtained using the Soave-Redlich-Kwong equation of state, which is proved to be the most accurate from previous work [2] when compared to the reference values from lit. [5].

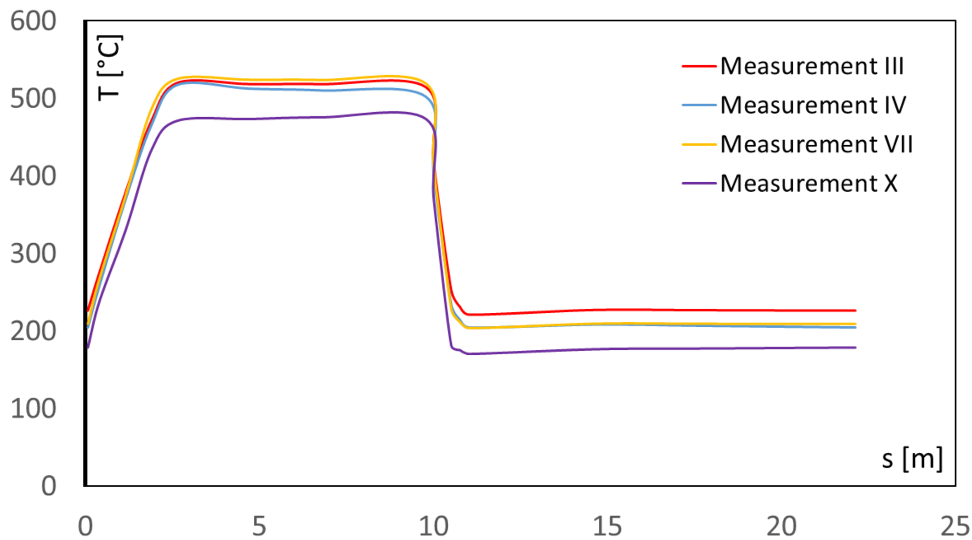

Fig. 3. The distribution of temperatures along the loop for four selected measurements.

Figure 3 shows the distribution of temperatures from measuring III, IV, VII and X during steady flow. The initial temperature is the value from the bottom of the cold branch (control point no. 4), then the values from the temperature sensors in the interior of GFR are displayed, continuing with hot branch and DHR. In the end, the value of cold branch is displayed again (from control point no. 4).

Figure 4 shows a record of mean velocity v_H in the hot branch from four measurements (III, IV, VII and X). The velocity is measured every 1 second and the total duration of measurements vary from 22000 [s] to 28000 [s]. Since the numerical model assumes a steady flow in the loop, it was necessary to select a range for all measurements, where steady state was considered as achieved. For the selected measurements the ranges were: Measurement III. (12500 – 18000) with average operating pressure 6.156 MPa, measurement IV. (15000 – 23000) with average operating pressure 5.730 MPa, measurement VII. (10000 – 17300) with average operating pressure 4.992 MPa, and measurement X. (10000 – 17000) with average operating pressure 3.423 MPa.

When compared, the measured and calculated velocity v_H has a similar course. The averaged deviation between the calculation and the measurements in the considered range of steady-state flow were satisfactory with the values for measurement III. – 4.964 %, measurement IV. – 4.520 %, measurement VII. – 6.311 % and measurement X. – 4.456 %.

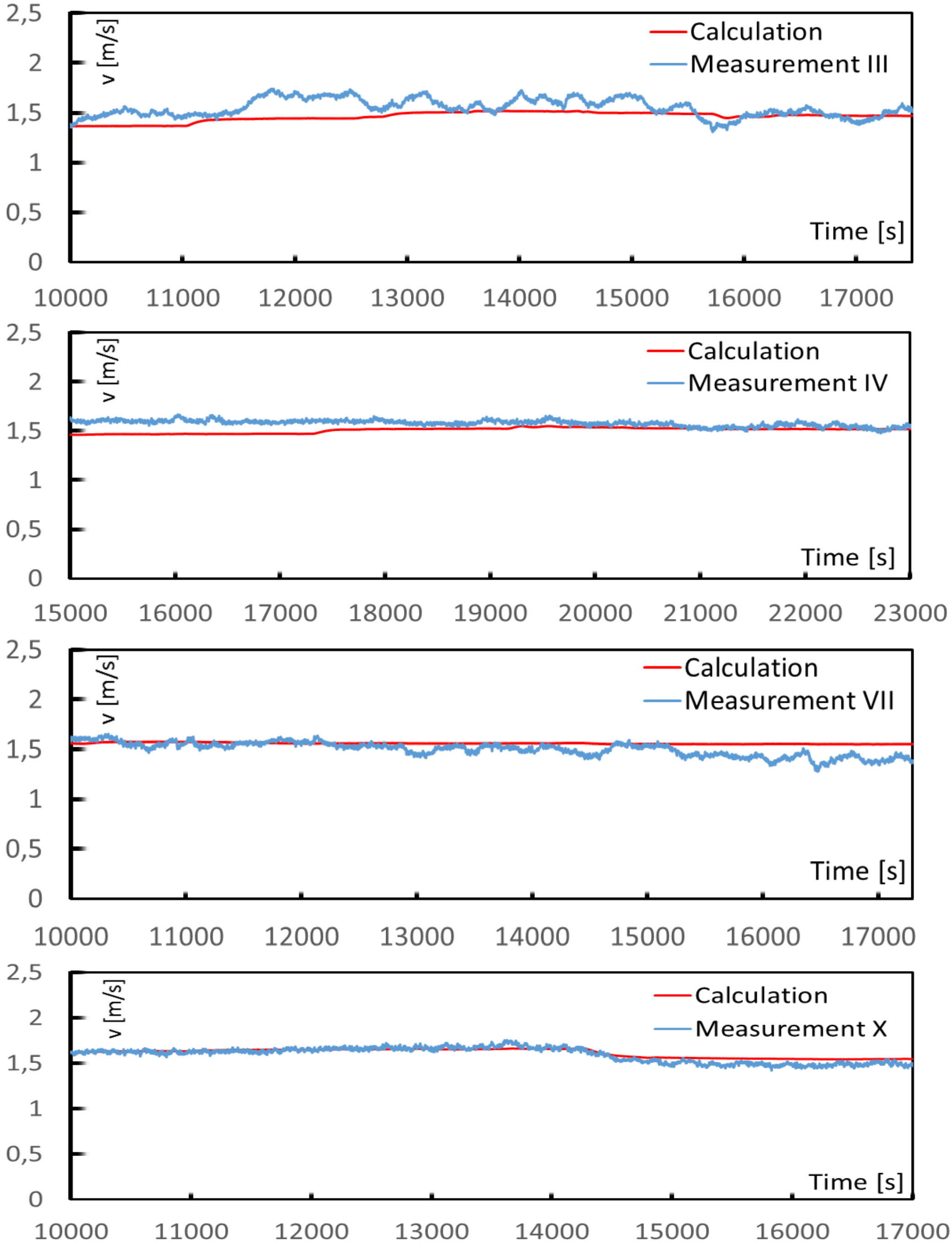

Fig. 4. Comparison of measured velocity (blue) with calculated values using numerical model (red).

5 Conclusion

The article analyses a one-dimensional numerical model of flow in the helium loop with natural circulation. The flow is described as one-dimensional and steady. It turns out that a one-dimensional model can describe the flow in such a facility with sufficient accuracy. The difference between the calculated values and the selected measurements were about 4 % – 7 %. The deviations are apparently because the one-dimensional model does not take into account the flow to the y-axis and in particular, does not consider the backflows and swirls that almost certainly occur when helium enters into the DHR. We want to address the backflow problem in our further research, as well as the enhancement of the current numerical model into a thermodynamic model, capable of calculating the temperature distribution in the loop. The thermodynamic model is expected to have impaired accuracy due to deviations in temperature calculations.

This contribution was created on the basis of the project "Research centre ALLEGRO” (ITMS project code: 26220220198), supported by Operational Programme Research and Development funded by the European Regional Development Fund.

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