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ESTIMATION OF MINOR LOSSES IN A NATURAL CIRCULATION HELIUM LOOP

F. Világi*, B. Knížat**, F. Urban***, R. Olšiak****, M. Mlkvik*****, F. Ridzoň******, P. Mlynár******

Abstract: *The article deals with steady flow of highly compressed helium in a natural circulation loop. To describe the mechanism of circulation, it is necessary to properly determine the losses which the functionality of the entire facility depends on. The biggest losses in the system are minor losses for the cooler and the heater. This article describes the way of defining minor losses in the elements at non-isothermal flow. The derived equations are used for evaluation of measurement of the cooler's minor loss (DHR), with installed input power of 500 kW, which is a crucial part of the experimental helium loop. The results are compared with calculations published in referenced literature. The process described leads to a derivation of minor loss coefficient of the DHR (i.e. the element with non-isothermal flow). The results obtained are necessary to develop an 1D model of flow in the loop.*

Keywords: Natural circulation, Helium loop, Minor losses, State equation.

1. Introduction

The helium natural circulation loop is a prospective facility for decay heat removal from a fast nuclear reactor. There is very intensive ongoing research in this field.

Helium, if used as a coolant, has several advantages over other methods of nuclear reactor cooling such as sodium or liquid metals. Helium has suitable chemical and physical properties because it is non-toxic and has high values of thermal conductivity and specific heat. This concept represents a safe method of emergency cooling of nuclear reactors. The faculty of mechanical engineering in Bratislava has built an experimental loop, under the Allegro project, for testing the behavior of naturally circulating helium. The facility has undergone a trial period and several experiments are ongoing. Some of the results are presented in this article.

2. Experimental facility

The diagram of the experimental facility is shown in Fig. 1. The facility is used for a research of heat transfer from the GFR device (substitute for a nuclear reactor). The piping circuit provides an opportunity for research and verification of thermodynamic and hydraulic properties of highly compressed naturally circulating helium. The facility consists of hot and cold piping branches, the heat source (the "GFR"

* Ing. František Világi.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, frantisek.vilagi@stuba.sk

** Assoc. Prof. Ing. Branislav Knížat, PhD.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, branislav.knizat@stuba.sk

*** Prof. Ing. František Urban, PhD.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, frantisek.urban@stuba.sk

**** Assoc. Prof. Ing. Róbert Olšiak, PhD.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, robert.olsiak@stuba.sk

***** Ing. Marek Mlkvik, PhD.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, marek.mlkvik@stuba.sk

****** Assoc. Prof. Ing. František Ridzoň, CScSlovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, frantisek.ridzon@stuba.sk

******* Ing. Peter Mlynár, PhD.: Slovak University of Technology in Bratislava, Nám. slobody 17, 812 31 Bratislava 1, SR, peter.mlynar@stuba.sk

device) and the cooler (the "DHR" device). The experimental facility enables adjustment of input and output power, temperatures and pressures of circulating helium. The steady and unsteady flow for a given range of operating conditions is also the subject of this research.

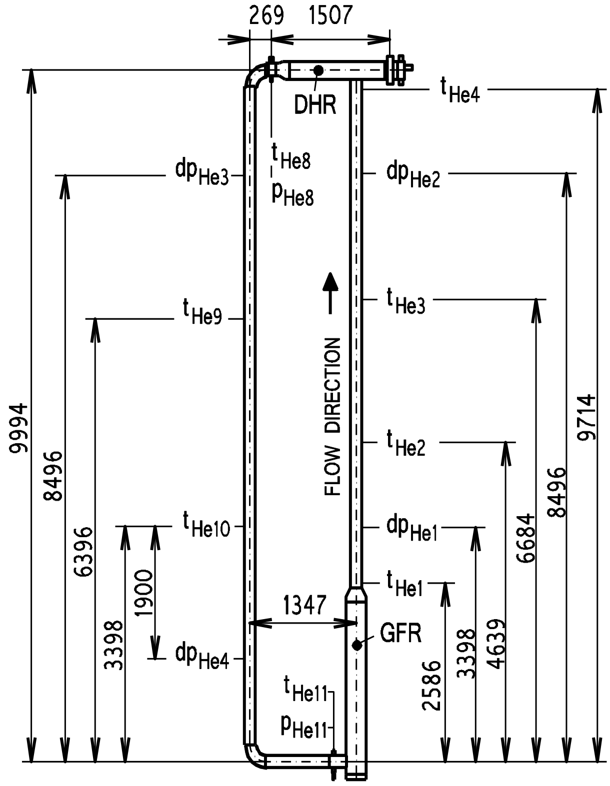

Fig. 1: Diagram of experimental facility.

In addition to the geometric information, the locations of sensors are also described in the diagram. The GFR device has a maximum installed input power of 500 kW. The facility encompasses an advanced system of automated collection and evaluation of measured data. Pressures, temperatures and pressure differences of devices are continuously measured at various locations of the piping circuit. The measurements of flow velocities are conducted by Pitot tubes (Urban et al., 2016). Since the radiation of the heat to the surroundings is generally neglected in pipe lines and will not be evaluated in this paper, the most crucial values for our calculations are the temperatures from the following sensors: t_{He1}, t_{He4}, t_{He8}, t_{He11} and the velocity values. For sufficiently accurate description of flow in a helium loop, it is necessary to know the resistance characteristics of the system. Therefore the purpose of the measurement was to determine the resistance characteristics of the GFR and the DHR devices.

3. Flow conditions

The flow in the pipes can be considered as isothermal because of very effective thermal insulation. However, the flow in the GFR and DHR devices is non-isothermal (Urban et al., 2016). Also, the helium compressibility along the loop can be neglected, because of relatively small pressure changes (maximum hundreds of pascals). According to the output power set-up of the devices and the operating pressure, helium can reach the following values:

- Temperature of He on the outlet: GFR: 400 ºC - 520 ºC
- Temperature of He on the inlet: GFR: 150 ºC - 250 ºC
- Operating pressure of He: 3 MPa - 7 MPa

To create a numerical model and to determine the resistance characteristics of devices it is very important to know the density of helium at critical points of the process. Thanks to continuous measurements, the temperature and pressure is a known value at any moment, so the density of helium can be calculated from the equation of state.

3.1. State properties

In order to make the most accurate determination of state properties, three methods of calculation were considered, which are commonly used to model the behavior of real gases. When comparing the results of our calculations, the data from (McCarty et al, 1998) were taken as reference values. Helium densities were calculated using three different methods for temperature range 300 – 800 K and pressure range 1.0 – 7.0 MPa. The first compared method was the Redlich-Kwong cubic equation of state, which has showed a maximum deviation of 5.8 %, the second method was the Benedict-Webb-Rubin equation, which showed a maximum deviation of 3.78 %. The third used method was the Soave-Redlich-Kwong, which exhibited a maximum deviation of only 0.47 %. This accuracy is sufficient for the calculation of thermal and hydraulic parameters. Therefore the calculation of density was carried out iteratively using the Soave-Redlich-Kwong state equation shown below (Novák, 2007):

$$p = \frac{RT}{V_m - b} - \frac{a}{V_m (V_m + b)} = \frac{\rho RT}{1 - b\rho} - \frac{a\rho^2}{1 + b\rho} \qquad (1)$$

$$a = 0.427482 \frac{R^2 T_C^2}{p_C} \alpha\, ; \; b = 0.008664 \frac{R\, T_C}{p_C} \qquad (2)$$

$$\alpha = \left[1 + m\left(1 - \sqrt{T_r}\right)\right]^2 = \left[1 + \left(1 - \sqrt{T_r}\right)\left(0.480 + 1.574\omega - 0.176\omega^2\right)\right]^2 \qquad (3)$$

In Eqs. (1 – 3), the critical temperature and pressure of the gas are identified as T_c, p_c, respectively. The acentric factor is ω and the reduced temperature is T_r calculated as: $T_r = T / T_c$. By further analytical integrations of general equations other thermodynamic properties such as enthalpy and heat capacity can be calculated. The deviation from the reference value for enthalpy was a maximum of 0.11 % and for heat capacity 0.16 %.

3.2 Transport properties

For calculation of the helium viscosity at various temperatures and pressures, the Sutherland law was used. As the accuracy of this law largely depends on the fluid used and can be inaccurate at higher pressures, the results had to be compared with reference values in (McCarty et al., 1998). The maximum deviation was 3.2 %. During flow calculations, viscosity is relevant only for the friction losses, which are extremely small because of low velocity, compared to the losses in the GFR and the DHR. Therefore the Sutherland formula provided sufficient accuracy.

4. Minor losses in the loop

The largest pressure loss occurs in the heater (GFR) and in the cooler (DHR). Therefore their estimation is the goal of this work. These losses are so-called "minor losses" in terms of fluid flow and a generally known formula applies to them:

$$\frac{\Delta p_m}{\rho} = \xi \frac{v^2}{2} \qquad (4)$$

The equation (4) makes it possible to calculate the coefficient of minor loss ξ, if the values of mean velocity v, density ρ and the pressure difference Δp_m are known. Since the flow in GFR and DHR is non-isothermal, the mean velocity and the pressure changes from inlet to outlet in both elements. Thus the coefficient of minor loss was calculated in relation to averaged values of the above parameters. Averaged mean velocity and averaged density for non-isothermal elements were introduced as:

$$v_{ie} = \frac{v_i + v_e}{2} \qquad (5)$$

$$\rho_{ie} = \frac{\rho_i + \rho_e}{2} \qquad (6)$$

where ρ_i, v_i are the density and mean velocity on the inlet, respectively. ρ_e, v_e are the density and mean velocity on the outlet, respectively. The equation for minor pressure loss was defined as:

$$\frac{\Delta p_m}{\rho_{ie}} = \xi \frac{v_{ie}^2}{2} \qquad (7)$$

Equation (7) was edited into:

$$\sqrt{\Delta p_m} = \sqrt{\zeta} \left(\sqrt{\frac{\rho_{ie}}{2}} v_{ie} \right) \qquad (8)$$

Equation (8) is a straight line with the slope $\sqrt{\zeta}$. This assumption was experimentally verified on the described facility. The velocities v_i, v_e, and the temperatures and pressures were measured on the inlet and outlet of the element. The densities on the inlet and outlet ρ_i, ρ_e were calculated using the state equation. The measured pressure difference of the element was also evaluated. The measured values for equation (8) are plotted for the cooler DHR in Fig. 2. Fig. 2 represents a summary of more than 6000 data points at different operating temperatures and pressures. The regression curve fitting shows that the calculated linear relationship given in (Urban et al., 2016) was confirmed. The minor loss coefficient ζ_{DHR} (the slope of the line is $\sqrt{\zeta_{DHR}}$) was determined from the regression equation.

The resulting value of minor loss coefficient was determined as $\zeta_{DHR} = 48.634$. A theoretical value of this coefficient was previously estimated as $\zeta_{DHR} = 55.307$ in the work (Urban et al., 2016).

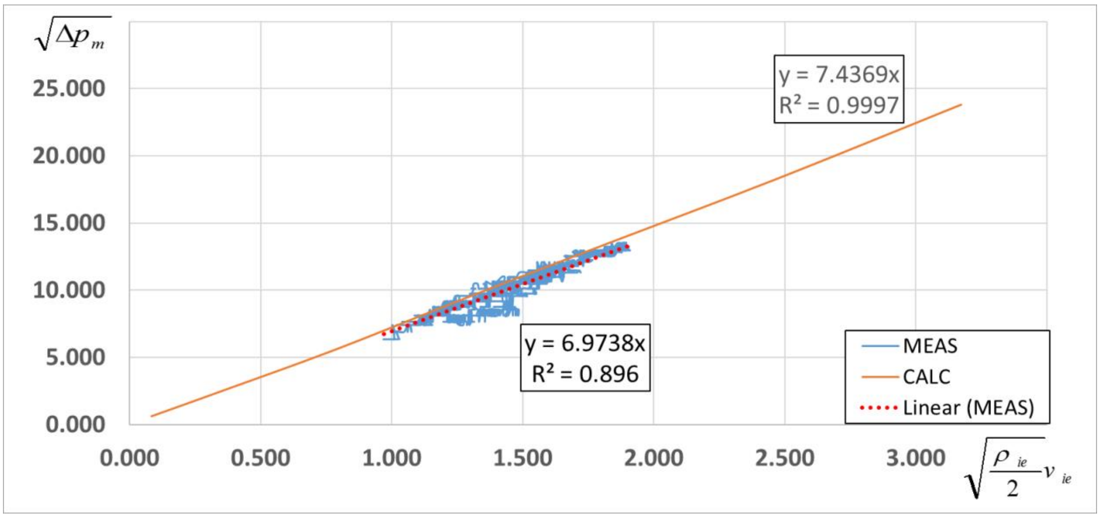

Fig. 2: Determination of minor losses in the DHR device.

5. Conclusions

The article presents a suggested expression of minor loss in the DHR cooler in the helium loop, intended for heat removal from the nuclear reactor substitute. General equation was modified and expressed in relation to averaged values of densities and mean velocities of the DHR element. This approach to local loss determination has proved very suitable. The expected linear relationship was proved by measurements on the helium loop at a wide range of operating conditions (more than 6000 measured points). It was possible to determine the coefficient of minor loss for the cooler from the regression curve. The measured relationship is in conformity with calculated values stated in (Urban et al., 2016). The results obtained are necessary to develop one-dimensional model of flow in the loop. Similar measurements will be conducted on the GFR device.

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