# Pressure drop in two-phase He I natural circulation loop at low vapor quality

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Steady state pressure drop in a two-phase He I natural circulation loop has been measured at atmospheric pressure. Results are obtained up to 0.2 exit vapor quality for a 14-mm diameter copper tube heated over a length of 1.2 m. Pressure drop assessment, done with the momentum balance equation including sub-cooling, reveals that the homogeneous model and Friedel's friction multiplier associated with Huq and Loth's void fraction correlations predict data within 15%.

## INTRODUCTION

The experimental study on the pressure drop in a two-phase He I natural circulation loop is a part of the cryogenic system design of the Compact Muon Solenoid at CERN. This work intends to find an accurate two-phase friction factor correlation for He I natural circulation flow up to an exit vapor quality of 0.2. Few pressure drop data are available in the literature for vertical helium boiling two-phase flow [1-3]; however, only in forced flow conditions. No data exist in the literature for natural circulation loop.

## EXPERIMENTAL SET-UP AND PRESSURE DROP MEASUREMENTS

The experimental facility consists of a vertical 2 m long cryostat composed of a liquid-vapor separator, a test section and its downward tube. A detailed description can be found in [4]. The heated section is made of a 1.2 m Cua1copper smooth tube with 14 mm inner diameter. Vapor mass flow is measured with a flow meter, capable of measuring up to 4.2 ± 0.01 g/s of He gas at room temperature. The liquid mass flow is measured by a 0.4 m long Venturi (40 mm entry and 10 mm neck diameters). It is equipped with Validyne pressure sensor calibrated at 4.2 K within ± 4 Pa. The precision on mass flow rate measurement varies from 10% at low mass flow rates to 2% at high mass flow rates. Pressure drop is measured with a room temperature 0-2 kPa range differential pressure sensor. Pressure taps are connected to the sensor with 2 mm diameter stainless steel tubes. Each tube is U-shaped and heated (0.1 W) to evaporate any residual liquid in order to avoid errors in pressure determination. Each pressure drop recording is averaged over 500 data points, and the standard deviation is around 5 Pa for all exit vapor quality range.

## DATA REDUCTION

The total pressure gradient along the tube can be defined by the momentum balance equation. In one dimension, this is expressed as the sum of the acceleration, gravitational and frictional terms,

$$\frac{dp}{dz}=\left(\frac{dp}{dz}\right)_{acc}+\left(\frac{dp}{dz}\right)_{gra}+\left(\frac{dp}{dz}\right)_{fric}. \qquad (1)$$

This method requires the knowledge of spatial distribution of the void fraction for the evaluation of the acceleration and gravitational terms and the wall shear stress for the frictional term. In our model, sub-cooling is included and the net vapor generation at the beginning of the two-phase region is assumed. Below this point, the flow is treated as a single-phase region from the thermodynamic point of view.

For the separated flow model, the total pressure drop is obtained by integrating Eq. (1) to take in account the void fraction variation along the tube,

$$\Delta p=\frac{G^2}{\rho_l}\left(\frac{x^2}{\alpha}\frac{\rho_l}{\rho_v}+\frac{(1-x)^2}{1-\alpha}-1\right)+\rho_l g h_b\left(1+\frac{h-h_b}{h_b}\frac{1}{x}\int_0^x \rho_v\alpha+\rho_l(1-\alpha)\,dx\right)+\frac{2C_f G^2}{\rho_l D}h_b\left(1+\frac{h-h_b}{h_b}\frac{1}{x}\int_0^x \phi_{TP}{}^2\,dx\right), \tag{2}$$

where $G$ is the mass flux, $x$ is the exit vapor quality, $\rho_l$ and $\rho_v$ are the liquid and vapor density, $\alpha$ is the void fraction, $g$ is the gravitational acceleration, $D$ is the tube diameter, $C_f$ is the liquid friction factor and $\phi_{TP}{}^2$ is the two-phase friction multiplier. $h_b$, the location on the z-axis where boiling occurs, is calculated from the energy balance equation while neglecting the kinetic term. It is expressed as,

$$h_b=\frac{\dot{m}Lx+\dot{m}Cp_l\Delta T_{sub}}{q\pi D-\rho_l g}, \tag{3}$$

where $\dot{m}$ is the total mass flow rate, $Cp_l$ is the specific heat of the liquid phase, $\Delta T_{sub}$ is the sub-cooling temperature difference, $q$ is the heat flux and $L$ is the latent heat of vaporization. Analytical integration of Eq. (1) is possible with assumptions that the compressibility of the gaseous phase is negligible and $\rho_l$, $\rho_v$ and $C_f$ remain constant over the tube length. For all correlations, $C_f$ is defined from the liquid Reynolds number as $C_f=0.184\ Re_l^{-0.2}$. For the homogeneous model, the pressure drop is a simplified version of Eq. (2) with the void fraction as given in Table 1.

As the void fraction is not measured in our experiment, it is preferable to compare total pressure drop data to Eq. (2) using different correlations. One finds that reducing data to determine $\phi_{TP}{}^2$ with void fraction correlations would bring in additional uncertainty because the total pressure drop is dominated by the void fraction evolution in this flow regime, and the frictional term is at most 20% of the gravitational pressure drop at the highest mass flux (G=139 kg/m$^2$s). For the total pressure drop calculation using the Chisholm and Friedel's correlations, a void fraction correlation is needed. We choose to use Levy's [5] and Huq and Loth's [6] correlations. The accuracy of Levy's model has been proven satisfactory in boiling He I forced flow [3], [7]. The latter is explicit and highly accurate at low vapor quality in comparison to the state-of-the-art correlations including two-phase boiling circulation flow data such as EPRI correlation [8]. The different correlations used in our calculation are listed in Table 1.

## MEASUREMENTS AND ANALYSIS

Figure 1 (a) presents the total pressure drop as a function of the exit vapor quality, $x$. This experimental study cover the ranges of $0\leqslant x\leqslant 0.21$, $0\leqslant q\leqslant 2268$ W/m$^2$ and $0\leqslant G\leqslant 139$ kg/m$^2$s. This curve is typical of two-phase boiling flow in natural circulation loop. At low exit vapor quality (low heat flux region for $q<500$ W/m$^2$) gravitational pressure drop dominates inducing a decrease of the total pressure drop. Since the void fraction is small in this region and so as the acceleration and frictional pressure drops, the total pressure drop is dominated by the evolution of the void fraction. One expects in this region the most accurate calculation with the most accurate void fraction correlation. At higher vapor quality, the frictional pressure term rises with the void fraction increase thus consequently slowing down the decrease in the pressure drop. This effect is not strong as we have already found in the total mass flow study [4] and it is probably due to the small difference in density of the two phases of helium.

Pressure drop assessment is presented as the ratio of measured to calculated $\Delta p$ versus $x$ in Figure 1 (c) and (d). All correlations considered here predict the measured total pressure drop within 30%, which is reasonable for two-phase flow, considering the simplicity of the model and that none of these correlations have been developed for the vapor-liquid helium mixture. This result is tempered by the fact that in our investigation range, the gravitational term is dominant and probably the easiest term to model. The frictional and acceleration $\Delta p$ never exceed 20% of the gravitational $\Delta p$. Except for the Lockhart-Martinelli correlation, the total $\Delta p$ is always over predicted, especially at high $x$, probably because void fraction is under predicted and the model is too crude to warrant better agreement with the data. Identical observations have been done for boiling forced flow calculation with the homogeneous model [2].

The closest assessment of the total pressure drop is achieved with the homogeneous model and the Friedel's combined with the Huq and Loth's void fraction correlations. The accuracy of homogeneous model is not surprising since the flow is in nucleate boiling regime up to x=0.15 [3,4]. The maximum deviation from the experimental value found with these models is lower than 15% at high exit quality (for $q>1000$ W/m$^2$) and few percent at lower exit quality. The result confirms that the void fraction correlation is the dominant factor for modeling such a flow, in the range cover by this experiment, because the calculated void fractions are identical for these two correlations as seen in Fig. 1 (b). Whatever the void fraction correlation used, it is interesting to notice that the Chisholm's and Friedel's correlations, which were built on extensive data sets including vertical boiling flow, do not give a better assessment than the homogeneous model even though these two correlations are based on the separated flow model and include in the two-phase friction multiplier definition, mass flux, diameter and physical property dependency. Our model does not take flow regime in consideration therefore this could also explain the discrepancy at high exit vapor quality ($x>0.15$), where partial burnout appears in the tube [4].

As expected, the largest disagreement is found with the Lockhart-Martinelli correlation where the deviation of the model from the experimental value can be as high as 30% (Fig. 1 (c)). This correlation also fails to model forced flow pressure drop results [2], possibly because it was build on air-water data. Obviously at low exit vapor quality, this correlation over estimates the void fraction and consequently the decrease of the gravitational term is erroneously high. It is confirmed in Figure 1 (b) where the Lockhart-Martinelli correlation gives the highest void fraction among the others. At higher $x$, the over estimated total pressure drop calculation implies that the frictional pressure drop is over evaluated. The Levy's model gives better accuracy than the Lockhart-Martinelli correlation but over estimates the total pressure drop by at most 20%. Since the void fraction correlation gives the lowest value as shown in Figure 1 (b),

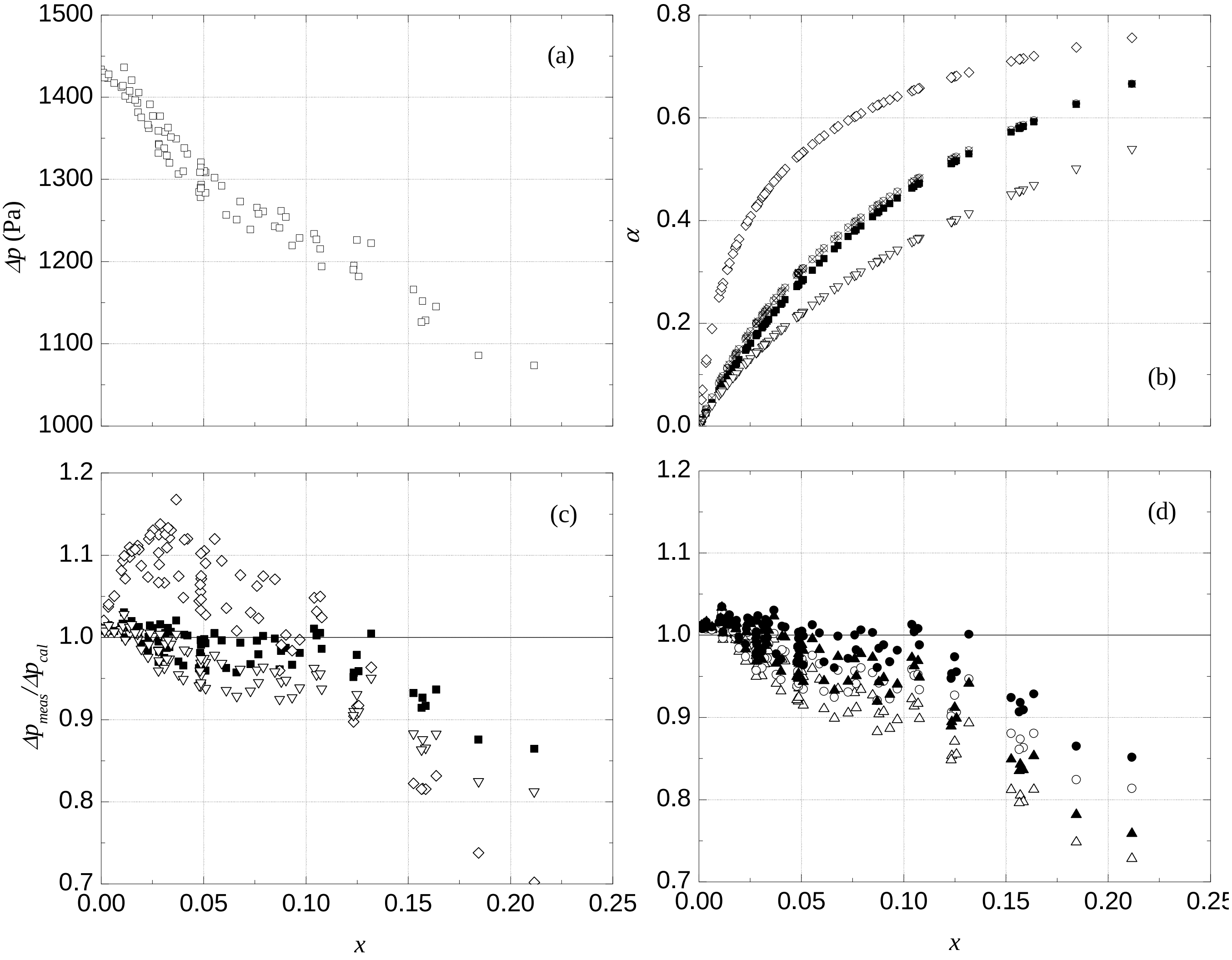

Figure 1 (a) Total pressure drop results
(b) Calculated void fraction $\alpha$ from experimental result as a function of the exit vapor quality, $x$
(c) Ratio of measured to calculated total pressure drop across the test section versus the exit vapor quality.
Calculation done with the homogeneous model: ■, the Lockhart-Martinelli's model: ◇ and the Levy's model: ▽
(d) Ratio of measured to calculated total pressure drop across the test section versus the exit vapor quality.
Calculation done with the Chisholm's: △, and the Friedel's: ○ correlation with Levy's void fraction correlation
Calculation done with the Chisholm's: ▲, and the Friedel's: ● correlation with Huq's void fraction correlation

Table 1 Correlations for void fraction and two-phase friction multiplier

| Correlation | Void fraction, $\alpha$ | Two-phase friction multiplier, $\phi_{TP}^2$ |
|---|---|---|
| Homogeneous model [9] | $\frac{x\rho_l}{x\rho_l+(1-x)\rho_v}$ | $\left(1+x\frac{\rho_l-\rho_v}{\rho_v}\right)\left(1+x\frac{\mu_l-\mu_v}{\mu_v}\right)^{-0.2}$ |
| Lockhart-Martinelli [10] | $1-(1+\frac{20}{X_{tt}}+\frac{1}{X_{tt}^2})^{-0.5}$ | $(1-x)^{1.8}(1+\frac{20}{X_{tt}}+\frac{1}{X_{tt}^2})$ where $\frac{1}{X_{tt}}=\left(\frac{x}{1-x}\right)^{0.9}\left(\frac{\rho_l}{\rho_v}\right)^{0.5}\left(\frac{\mu_v}{\mu_l}\right)^{0.1}$ |
| Levy [5] | Eq. (17) from [5] | $(1-x)^{1.75}/(1-\alpha)^2$ |
| Chisholm [11] with | - Levy [5], Eq. (17)<br>- Huq and Loth [6]<br>$1-\frac{2(1-x)^2}{1-2x+(1+4x(1-x)(\frac{\rho_l}{\rho_v}-1))^{0.5}}$ | $1+(\Gamma^2-1)(Bx^{0.9}(1-x)^{0.9}+x^{1.8})$<br>with $\Gamma^2=\frac{\rho_l}{\rho_v}\left(\frac{\mu_l}{\mu_v}\right)^{0.2}$<br>and $B=4.8$ since $\Gamma\leqslant 0.95$ and $G\leqslant 500$ kg/m$^2$s |
| Friedel [12] with | - Levy [5], Eq. (17)<br>- Huq and Loth [6]<br>$1-\frac{2(1-x)^2}{1-2x+(1+4x(1-x)(\frac{\rho_l}{\rho_v}-1))^{0.5}}$ | $(1-x)^2+x^2\frac{\rho_l}{\rho_v}\frac{f_{vo}}{f_{lo}}+\frac{3.21x^{0.78}(1-x)^{0.224}}{\left(\frac{G^2}{gD\rho^2}\right)^{0.0454}\left(\frac{G^2D}{\rho\sigma}\right)^{0.035}}\times$<br>$\left(\frac{\rho_l}{\rho_v}\right)^{0.91}\left(\frac{\mu_v}{\mu_l}\right)^{0.19}\left(1-\frac{\mu_v}{\mu_l}\right)^{0.7}$ |

$f_{vo}$ and $f_{lo}$ are the all vapor and all liquid friction factor, $\sigma$ is the surface tension and $\rho$ is the homogeneous void fraction

this model over predicts the gravitational term as the exit vapor quality increases. It should be noted that Levy's model does not give a more accurate prediction than the homogeneous model even though the void fraction correlation is in good agreement with helium data in forced flow conditions [3], [7].

## CONCLUSIONS

In the ranges cover by the experiment $0\leqslant x\leqslant 0.21$ and $0\leqslant q\leqslant 2268$ W/m$^2$, all correlations agree with experimental results within 30%. The most accurate assessment are obtained with the homogeneous model and the separated flow model with the Friedel's friction multiplier correlation and Huq and Loth's void fraction correlation. For simplicity, it is recommendable to use the homogeneous model to calculate the two-phase pressure drop in helium natural circulation loop for the ranges cover by this experiment.

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