Study of nitrogen two-phase flow pressure drop in horizontal and vertical orientation

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Abstract. The large-scale liquid argon Short Baseline Neutrino Far-detector located at Fermilab is designed to detect neutrinos allowing research in the field of neutrino oscillations. It will be filled with liquid argon and operate at almost ambient pressure. Consequently, its operation temperature is determined at about 87 K. The detector will be surrounded by a thermal shield, which is actively cooled with boiling nitrogen at a pressure of about 2.8 bar absolute, the respective saturation pressure of nitrogen. Due to strict temperature gradient constraints, it is important to study the two-phase flow pressure drop of nitrogen along the cooling circuit of the thermal shield in different orientations of the flow with respect to gravity. An experimental set-up has been built in order to determine the two-phase flow pressure drop in nitrogen in horizontal, vertical upward and vertical downward direction. The measurements have been conducted under quasi-adiabatic conditions and at a saturation pressure of 2.8 bar absolute. The mass velocity has been varied in the range of \(\frac{\text{kg}}{\text{m}^2\cdot\text{s}^{-1}}\) to \(70\ \frac{\text{kg}}{\text{m}^2\cdot\text{s}^{-1}}\) and the pressure drop data has been recorded scanning the two-phase region from vapor qualities close to zero up to 0.7. The experimental data will be compared with several established predictions of pressure drop e.g. Mueller-Steinhagen and Heck by using the void fraction correlation of Rouhani.

1. Introduction
The thermal shield cooling concept of large-scale liquid argon based detectors is focusing on nitrogen two-phase flow. The orientation of cooling tubes with respect to gravity influences the resulting pressure drop and the respective temperature change along the cooling panel length. Typical dimensions of the detectors are several meters causing the necessity of large thermal shield arrays to fully cover the external surface of the detector volume to drastically reduce the heat inleak into the detector liquid argon reservoir. Due to the detector dimensions, this reservoir needs to be operated close to ambient pressure, which determines the operating cooling conditions of the nitrogen two-phase flow at a saturated temperature and pressure of 87 K and to 2.8 bar absolute, respectively [1].

Essential parameters that determine the pressure drop in the cooling tubes are the vapor quality, flow pattern, and void fraction [2, 3]. As the mechanisms of two-phase flow have not been fully understood yet most phenomena are described by empirical correlations [4, 5]. It makes it difficult to use these correlations for other applications since they were originally developed for, e.g. different fluid properties, mass flow ranges or pipe diameter. Applying selected void fraction correlations and pressure drop models [5-9] to boiling nitrogen at the conditions of the large-scale detector thermal shields show rather high deviations; therefore, underscoring the need for a study of nitrogen two-phase flow at those specific conditions.
2. Experimental set-up

The design point of the nitrogen two-phase flow cooling is a flow rate of 2 g·s⁻¹ based on an 11 m long thermal shield panel. The chosen diameter of the cooling panel tube in the detector is 10 mm, leading to a mass flux of around 26 kg·m⁻²·s⁻¹. The experimental set-up is designed to enable mass flux values ranging from 20 kg·m⁻²·s⁻¹ to 70 kg·m⁻²·s⁻¹ by using a 6 mm inner tube diameter, see figure 1. The mass flow of saturated liquid nitrogen is conditioned from a Dewar at 4 bar absolute, subcooled to 78 K by using a precooling heat exchanger cryostat and finally adjusted to the inlet test section condition by a heater followed by a Joule-Thomson (J-T) expansion, see figure 1.

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**Figure 1.** Process and instrumentation diagram of the experimental set-up. The preconditioning of the nitrogen flow starts from a mobile Dewar of 500 l (point 1) via the pre-cooler to 78 K (point 3-4) and the heater EH01 to point 5 before the J-T expansion takes place into the two-phase range. The heater EH02 after the J-T valve enables the stepwise adjusting of the test section inlet vapor quality from point 6 to 7. The measurement sections are 7-8 for horizontal direction, 9-10 for vertical upward and 11-12 for vertical downward flow. Included is a detailed drawing of the experimental test section, which is placed in the vacuum environment and an adapted thermal shield to measure pressure drop in horizontal (3.2 m long spiral), vertical upward (1 m) and vertical downward (1 m) direction of the flow.
The inlet enthalpy and vapor quality can be determined by measuring the subcooled liquid temperature and pressure before the J-T expansion. The measured section itself is assumed to be adiabatic by insulating it inside a vacuum of $10^{-5}$ mbar and enclosing it with an outer thermal shield that is cooled to the sample temperature by the exhaust flow. The test section itself is conditioned by an additional heater that allowed to adjust the inlet vapor quality in a stepwise manner from 0.005 to about 0.7. The precision of vapor quality measurement for typical mass flow rates of $1 \text{g} \cdot \text{s}^{-1}$ is estimated by maximum error propagation of all measures to be 0.15% up to 8.6% for respective vapor qualities of 0.005 to 0.7. The corresponding pressure drop values were measured with differential pressure sensors outside of the vacuum enclosure. The pressure probing location at the test section is realized by four circumferentially placed points, which are hydraulically connected to the measurement capillary and thermally controlled by a Pt100 temperature sensor acting also as a small heater to check for and avoid thermal instabilities inside the capillary. The uncertainty of the pressure drop data was estimated to be $\Delta(\Delta p) = \pm 0.22 \text{ mbar}$.

3. Results and discussion

The nitrogen two-phase flow pressure drop has been determined at different vapor qualities and different mass flows, scanning the two-phase region from vapor qualities close to zero up to vapor qualities of up to 0.7. The reachable value of the vapor quality has been limited at high mass flows by the 120 V power supply of the preheater EH02 in front of the test section and at low mass flows by the beginning of dry-out, observable by a sharp increase of test section outlet temperature TTN05 [11], compare figure 1. Measurements at nine different mass flows have been performed. The mass flow is converted into the mass velocity with the pipe’s cross-section to obtain a quantity that is independent of the design of the measurement set-up. The small increase of the vapor quality inside the test section, even under adiabatic conditions owing to the pressure drop over the test section length, is taken into account. The measured pressure drop of each part is always plotted versus the average vapor quality of the part of the test section. However, the changes of the vapor quality due to pressure drop are only visible in the third or fourth digit after the decimal point.

3.1. Pressure drop in horizontal orientation

In horizontal flow conditions the frictional pressure drop is the main contribution to the total pressure drop, see figure 2. The pressure drop is positively correlated with the vapor quality owing to the increased interaction between the liquid and the vapor phase for vapor qualities higher than about 0.2. At low mass velocities, the pressure drop increases only slightly with the vapor quality, but the higher the mass velocity the steeper the pressure drop rises. At vapor qualities lower than 0.2, it seems, despite the noise of the pressure drop signal, that the pressure drop is constant or decreases slightly with increasing vapor quality. Moreover, the pressure drop rises with higher mass velocity. The difference between the pressure drop at different mass velocities becomes more distinct at higher vapor qualities and higher mass velocities. The latter effect resembles the quadratic dependence of the frictional pressure drop on the mass velocity known from single-phase flow. The behavior of the pressure drop at horizontal flow could be explained by flow regime transitions [12]. Only if the flow is in the stable annular flow regime, the pressure drop increases significantly with the vapor quality. For example, for a mass velocity of $35 \text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ the flow reaches the annular flow regime for vapor qualities higher than 0.4. That predicted change in flow pattern corresponds well with the clear increase of the pressure drop in figure 2. If the mass velocity is higher, the annular flow regime is entered at a lower vapor quality and the pressure drop curve rises earlier.
Figure 2. Graph showing the pressure drop vs. vapor quality of nitrogen two-phase flow in horizontal orientation for the 3.2 m long part of the test section. The best fitting void fraction correlation for the studied dependencies from Rouhani [5], applied to the pressure drop model of Mueller-Steinhagen and Heck [7], is shown in the graph as dotted lines. The two distinct pressure drop behaviors are caused by the change of flow pattern following Taitel and Dukler [11] from stratified (wavy) flow to annular flow depending on mass velocity between 0.15 up to 0.4.

3.2. Pressure drop in vertical upward orientation

In vertical upward flow orientation the gravitational pressure is the main contribution to the total pressure drop, see figure 3. The gravitational pressure drop reduces with increasing vapor quality, as the average density is reduced with increasing vapor quality. The pressure drop decreases steeply up to vapor qualities of about 0.1, then it declines more moderately, as the change of the void fraction with the vapor quality is more distinct at low vapor qualities. The influence of the mass velocity on the pressure drop is not as pronounced as in the case of horizontal flow, the pressure drop differences between the different mass velocities are small. Up to vapor qualities of about 0.3 the differences of measured pressure drop between the mass velocities are marginal by also taking into account the error of the measurement signal. For vapor qualities greater than 0.3 a trend of higher pressure drop for lower mass velocities is visible. Rouhani’s correlation predicts for low vapor qualities high pressure drop values, including a steep decrease of the pressure drop at vapor qualities from 0 to 0.2. It over-predicts the pressure drop at low vapor qualities compared to the measured data. For the planned scaling to the thermal shield of the large scale detector, the focus is on the accurate prediction of the pressure drop at vapor qualities higher than 0.1 (stable inlet conditions in the two-phase range by J-T expansion). The pressure drop at low vapor qualities up to 0.1 to 0.15 is better reproduced by the Crisholm correlation [9], but it underpredicts the pressure drop for all higher vapor qualities, what is not shown here. Interestingly, all void fraction correlations taking into account a dependency of the void fraction on the mass velocity, tend to overpredict the pressure drop, especially at low vapor qualities up to 0.1. On the contrary, all void fraction correlations neglecting a dependency of the void fraction on the mass velocity, succeed to predict the pressure drop of the measurement data at low vapor qualities up to 0.1 better, but strongly underestimate the pressure drop at higher vapor qualities [10].
3.3. Pressure drop in vertical downward orientation

Figure 4 shows the pressure drop measured in the 1 m long vertical downward part of the test section versus the vapor quality for nine different mass velocities. In vertical downward flow the gravitational pressure drop should be, in theory, the main contributor to the total pressure drop, resulting in a pressure gain for downward flow. However, as can be seen in figure 4, the pressure drop for all mass velocities and over the whole range of vapor qualities is close to zero. Only at low vapor qualities smaller than 0.1, despite the noise of the signal, the measurement data suggest a small pressure gain. This observation confirms the statement of Beggs [12], who claims that the gravitational pressure drop must not be included into the total pressure drop for vertical downward flow. It seems that the effect of a pressure gain during vertical downward flow, as it is quite known from single phase liquid flow, is eliminated when only a few bubbles are formed granted that buoyancy forces counteract the gravitational forces. At higher vapor qualities as well as higher mass velocities the rising frictional pressure drop is the main contributor to the overall pressure drop. It is clearly visible in figure 4 that the pressure drop model fails to predict the values of the vertical downward part of the test section when applying the Rouhani correlation for the void fraction and the Mueller-Steinhagen and Heck model for the frictional pressure drop. All the other void fraction correlations also fail, what is not depicted here. All pressure drop models predict a gradual decrease with increasing vapor quality. Instead, in our measurements we have observed that the pressure drop diminishes the moment the flow is in the two-phase region. This unexpected behavior of the pressure drop at vertical downward flow orientation is further investigated hereafter.
Figure 4. Graph of the measured nitrogen two-phase pressure drop in the 1 m long vertical downward part of the test section versus the vapor quality for nine different mass velocities. Comparison of the measurement data (markers) for the pressure drop in the vertical downward part with the calculated pressure drop (dotted lines), applied void fraction correlation: Rouhani [5] and pressured drop model from Mueller-Steinhagen and Heck [7].

3.4. Comparison of pressure drop behavior

In order to validate the measurement data, especially in the vertical downward direction and at low vapor qualities, the pressure drop in liquid flow has been measured. Subsequently, the flow has been directly heated into the two-phase region with heater EH02 (needle valve completely open) and the response of the differential pressure transmitters have been observed. Figure 5 shows the course of the differential pressure for all three parts of the test section as well as the course of the inlet temperature of the test section TTN03 versus time. The step function of the applied heating power is shown by the calculated enthalpy of the flow. The horizontal line indicates the enthalpy at the boiling point at the bottom of the graph. At the beginning of the measurement the test section preheater EH02 is off and the flow at a pressure of about 2.8 bar and at a temperature of about 82 K is in the subcooled liquid phase. As can be seen, the frictional pressure drop in the horizontal part of the test section is, as expected, extremely small. The pressure loss in the vertical upward part and the pressure gain in the vertical downward part are the same around 70 mbar, according to the absolute value, and also corresponding to the expected value in liquid flow. The heating power of EH02 is stepwise increased until a vapor quality of 0.086 is reached. The temperature rises from time step 0.28 h onwards fitting to the heating step to reach the two-phase region. According to nitrogen fluid properties, the saturation temperature corresponding to the saturation pressure of 2.8 bar is about 87 K. One can observe that, the condition of the flow barely reaches the two-phase region at t=0.48 h, when first bubbles are formed in the preheater, the pressure gain in the vertical downward part increases directly to a value close to zero. The pressure loss in the vertical upward part drops as well when the two-phase conditions are reached but it drops in a more moderate way by taking several minutes to reach steady state values for constant applied preheater power. All pressure drop values are showing a consistent behavior for slightly higher vapor quality steps (maximum vapor quality in this test campaign is 0.086) corresponding to the earlier described dependencies.
Figure 5. Graph of the behavior of the pressure drop in all three parts of the test section while applying stepwise heating from single-phase flow into two-phase flow region. Two-phase flow conditions are considered to be reached when temperature TTN03 (inlet of the test section) is approaching 87 K at around t=0.5 h. The calculated enthalpy of the flow represents the step function of the applied heater power of the test section preheater EH02. The horizontal dashed line indicates the enthalpy at the boiling point. The vertical dashed lines give a guide to the eye when the flow is in subcooled liquid or in the two-phase region. Measurement conditions are: p=2.8 bar, G=51.3 kg·m⁻²·s⁻¹.

When the heater power is reduced again, mirror-inverted to increasing the preheater power, first the pressure drop in the vertical upward part sharply increases again, whereas the pressure gain on the vertical downward part rises with some time delay. In summary, two observations can be made. Firstly, the pressure gain in vertical downward flow can be measured correctly with the experimental set-up for liquid flow, proving that the pressure gain in vertical downward two-phase flow is negligible. Secondly, entering the two-phase area by heating causes delay in boiling and the flow is not in thermodynamic equilibrium as for vertical upward flow. The same pressure drop values as in liquid flow are measured at a time when the flow is in subcooled liquid or in the two-phase region. The measurement data for the pressure drop in vertical upward flow at low vapor qualities is lower than the predicted one, because in the measurements described before the two-phase area is entered by a J-T expansion forcing the flow instantly into thermodynamic equilibrium. This is one possible explanation for the differences for low vapor quality described by the models and former studies and the here presented measurement data.

4. Conclusion
An experimental set-up has been built in order to determine the two-phase flow pressure drop in nitrogen in a horizontal, vertical upward and vertical downward part. The measurements have been conducted under quasi-adiabatic conditions and at a pressure of 2.8 bar. The mass velocity has been varied in the range between 20 kg·m⁻²·s⁻¹ and 70 kg·m⁻²·s⁻¹. The two-phase area is scanned from a vapor quality close to zero up to 0.7 depending on the total mass flow rate. At that conditions, chaotic flow occurs in the vertical parts of the test section, whereas the flow in the horizontal part can be located in the stratified, wavy or annular flow regime, depending on the vapor quality and the mass velocity. In horizontal flow, the frictional pressure drop accounts for the largest contribution to the total pressure drop. For vapor
qualities higher than 0.2 the pressure drop is positively correlated with both, the vapor quality and the mass velocity. In vertical upward flow orientation, the gravitational pressure drop is the largest contributor to the total pressure drop. The pressure drop reduces with increasing vapor quality showing a sharp decline at low vapor qualities. The dependency of the pressure drop on the mass velocity is not as pronounced as in horizontal flow. In vertical downward flow the pressure drop is close to zero over the whole tested range of vapor qualities and mass velocities. It seems, when the first vapor bubbles are formed, the gravitational pressure gain, well-known from single-phase liquid flow, is eliminated. A numerical program has been developed, which computes the two-phase pressure drop of boiling nitrogen in the range of saturation pressures of 2.6 bar to 2.9 bar by coupling the momentum and energy equations, details can be found [10]. By comparing the experimental data with the calculated data, it can be pointed out, that the void fraction correlation of Rouhani and the frictional pressure drop model of Mueller-Steinhagen and Heck fit best the studied nitrogen two-phase pressure drop in horizontal and vertical upward flow.

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