Cryogenic Pipe Flow Simulation for Liquid Nitrogen

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ABSTRACT

Cryogenics is dealing with very low temperatures of less than 120 K. Applications of cryogenic can be found in variety of fields such as physics, chemistry, biology, medicine, engineering and industry. Cryogenic pipe flow is very different compared to normal fluid pipe flow in terms of evaluation and analysis in terms of fluid state change caused by heat leak in cryogenics during transportation in transfer line. The present study is on liquid nitrogen pipe flow simulation in order to understand the flow characteristic and temperature distribution in the pipe flow. Computational fluid dynamics (CFD) software has been employed for the present study. The 3-dimensional liquid nitrogen pipe flow simulation has been conducted using ANSYS FLUENT to obtain the flow characteristic and temperature distribution. The turbulent liquid nitrogen pipe flow has been simulated and the flow velocity and the temperature distribution have been obtained. As a result from the simulation, the temperature distribution shows the temperature of the flow exceeds the normal boiling point of liquid nitrogen (77.347 K) and this leads to state changing from liquid to vapour and turning the flow into two phase flow. In order to have the desired flow velocity of less than 1 m/s for pipe size of 22.1 mm inner diameter and 1 m length, the inlet volume flow rate should not be more than 500 LPH (litre per hour) as per simulation results.

Keywords: *Cryogenic, Thermal Insulation System, Liquid Nitrogen, Pipe Flow*

ISSN 1823-5514, eISSN 2550-164X

Received for review: 2016-04-20
Accepted for publication: 2017-02-01
Published: 2017-06-01

Introduction

Cryogenics is a branch of physics dealing with the production and effects of very low temperatures of less than 120 K (−153 °C; −243 °F) [1], although this historical summary does not adhere to a strict 120 K definition [2]. With the use of cryogenics, it is possible to store a lot of matters in a very small space with very high energy density. Applications of cryogenic can be found in variety of fields such as physics, chemistry, biology, medicine, engineering and industry. Cryogenic technology gained widespread recognition during the 1960s with emphasis on cryogenic techniques, cooling system installation configurations, and applications [3].

Thermal insulation is a key to minimize heat leak in cryogenics during transportation in transfer line, which is extremely important in cryogenics that deal with very low temperature apparatuses and experiments. Efficient thermal insulation determines the cost effectiveness in cryogenics transfer line. The most important advancement in cryogenic insulation over the past 50 years has been the development of multilayer insulation (MLI) [4]. The most efficient and best matched to cryogenic conditions is a multilayer vacuum insulation (MLI) as per study done by Chorowski and Polinski [5]. Designing an effective thermal insulation for cryogenic transfer line is a complex study.

Piping system sizing for a desire cryogen flow rate is a typical problem because of the fluid state change along the flow journey [6]. Studies on cryogenic transfer lines have regained importance in recent times with the growth of large-scale applications of superconductivity and the needs of space programmes [7, 8].

Liquid nitrogen

Liquid nitrogen (LN2) is one of the cryogens. LN2 is obtained from air in large liquefaction and separation plants. LN2 is a cheap and safe source of cold and it is able to maintain temperatures far below the freezing points of water. This makes it extremely useful in wide range of applications such as in freezing of food, pressurization of plastic bottles and aluminium cans containing drinks, fixing of pipelines by freezing the liquid on either side of the leak, ground freezing, deflashing of moulded polymer products, heat treatment of metals, working of solid explosive and bomb disposal, cooling of cold traps in vacuum systems, cryo-cleaning and so on. LN2 is commonly used in the pre-cooling of cryogenic equipment due to its high latent heat of evaporation [9].

LN2 boils at 77 K (−196 °C; −321 °F) and freezes at 63 K (−210 °C; −346 °F), and to maintain it in the liquefied form is difficult as there is continuous boil off due to heat in leaks, especially in the ambient temperature (300 K) that is quite high compared to its boiling temperature (77 K). The liquid nitrogen boils off continuously due to various modes of heat transfer. LN2 is a very efficient coolant but limited by the Leidenfrost effect. Leidenfrost effect is the formation of a gas barrier between a hot surface and a boiling liquid if the temperature gradient is great enough. LN2 is a compact and readily transported source of nitrogen gas without pressurization. LN2 is a fairly inert gas medium and has unique properties that makes it the most ideal space simulation chamber with cold drawing of stainless steel used in specific industrial and scientific research applications [3]. Thermodynamic properties of liquid nitrogen (LN2) and selected properties of liquid nitrogen at the normal boiling point are shown in Table 1 and Table 2 respectively.

Table 1: Thermodynamic Properties of Liquid Nitrogen [9]

Property	**Value**
Boiling point temperature at p = 1 bar, Tbp (K)	77.4
Melting temperature at p = 1 bar, Tm (K)	63.3
Triple point temperature, Ttr (K)	63.2
Triple point pressure, ptr (104 Pa)	1.3
Critical point temperature, Tcr (K)	126.2
Critical point pressure, pcr (MPa)	3.4
Inversion temperature, Ti (K)	621.0
Inversion pressure, pi (105 Pa)	380.0
Latent heat of vaporization at Tb (kJ/L)	160.0
Volume % in air	78.1

Table 2: Selected Properties of Liquid Nitrogen at the Normal Boiling Point [10]

Property	**Value**
Normal boiling point (K)	77.4
Density (kg/m3)	808.9
Heat of vaporization (kJ/kg)	198.3
Specific heat (kJ/(kg K) ×10-1)	20.4
Viscosity (kg/(ms)×106)	157.9
Thermal conductivity (mW/(m K))	139.6
Dielectric constant	1.4
Critical temperature (K)	126.2
Critical pressure (MPa)	3.4
Temperature at triple point (K)	63.1
Pressure at triple point (MPa×103)	12.5

Heat transfer in cryogenic

The heat transfer processes in cryogenics are basically the same as for any engineering temperature range. Heat transfer at low temperatures is governed by the same three mechanisms present at ambient and elevated temperatures: conduction, convection, and radiation. Therefore, all the general equations are appropriate for low-temperature applications as long as they are adjusted for the property changes in both materials and fluids [10].

Heat transfer depends on the operating parameters, flow pipe cross-sectional geometry (circular or rectangular or square), and fluid flow types such as laminar, turbulent, or transient [3]. Heat transfer properties for a linear flow are quite different from those for a turbulent flow or transient flow. Under the turbulent flow environments, the flow will be treated as a non-homogenous flow; therefore, nonlinear flow equations will be involved in the thermal analysis of heat exchangers. The rotation of the tube carrying the fluid does not affect the laminar flow resistance once the established cooling flow exists. However, under the turbulent flow conditions, flow resistance undergoes radical change.

Figure 1 shows the typical design of vacuum insulated pipe (VIP) recommended by the industry partner, Cryogas Tech [11]. The outer pipe temperature as the ambient temperature is 300 K (27˚C) and the inner pipe temperature as the liquid nitrogen temperature is 77 K (-196˚C). Since there is temperature difference between outer pipe and inner pipe, the heat transfer is in the direction of decreasing temperature which is from outer pipe to inner pipe. This means the heat flows into the pipe containing cryogenic fluid.

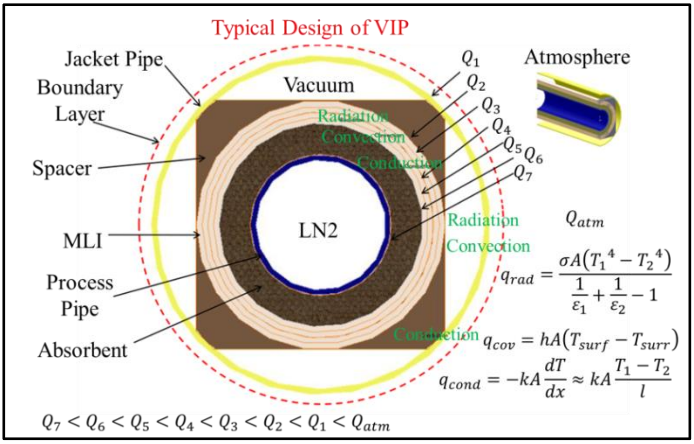


Figure 1: Typical Design of Vacuum Insulated Pipe (VIP) [11]

Computational fluid dynamics (CFD)

Computational fluid dynamics (CFD) is the analysis of systems involving fluid flow, heat transfer and associated phenomena such as chemical reactions by means of computer-based simulation [12].

The physical aspects of any fluid flow are governed by the following three fundamental principles: mass is conserved; Newton's second law; and energy is conserved. These fundamental principles can be expressed in terms of mathematical equations, in which their most general form is usually partial differential equations. Computational fluid dynamics (CFD) is, in part, the art of replacing the governing partial differential equations of fluid flow with numbers, and advancing these numbers in space and/or time to obtain a final numerical description of the complete flow field of interest [13].

In recent years, researchers have been dedicated to study the flow characteristics and heat transfer of cryogen with either numerical analysis or computational fluid dynamics (CFD) or both.

Simulation Model

Liquid nitrogen pipe flow model

Figure 2 shows the liquid nitrogen pipe flow model for the present study. The SS304 process pipe outer and inner diameters for the typical design of VIP are 25.4 mm and 22.1 mm respectively [11]. The present study will model the liquid nitrogen pipe flow in the 1 m pipe length of process pipe without the insulation for simulation.

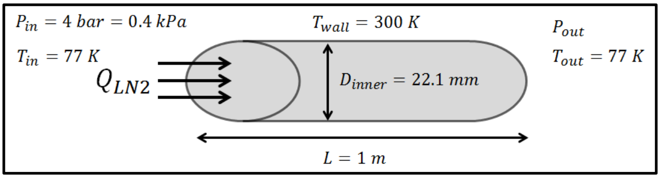


Figure 2: LN2 pipe flow model

ANSYS FLUENT simulation

For the geometry of fluid domain, half sectional pipe was created by ANSYS DesignModeler. ANSYS FLUENT simulated the fluid flow thought a solid surface which means the geometry of piping's internal structure has been modelled as solid. Three dimensional (3-D) model of a half sectional pipe with an asymmetric plane was created.

The fluid inlet diameter as the inner diameter of the process pipe was taken as 22.1 mm and the pipe length as 1 m. Figure 3 below shows the 3-D layout of the half-sectional pipe created by ANSYS DesignModeler.

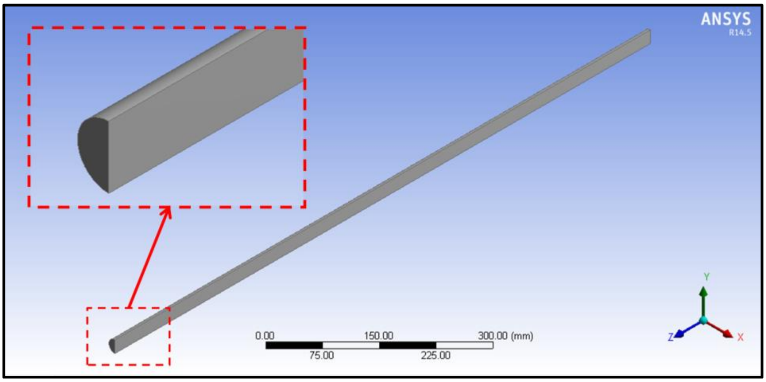


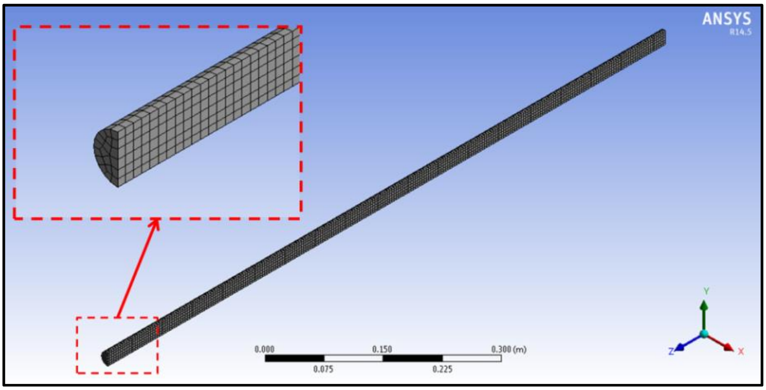
Figure 3: 3-D Layout of the half-sectional pipe in ANSYS DesignModeler (Isometric view)

By considering the maximum inlet velocity as 1 m/s, the calculated Reynolds number was up to 110.89×10^3 (>4000). The flow condition of liquid nitrogen pipe flow will be turbulent flow. In ANSYS FLUENT, the turbulence model of k-epsilon model was used for the liquid nitrogen pipe flow that enables the energy equation for the simulation.

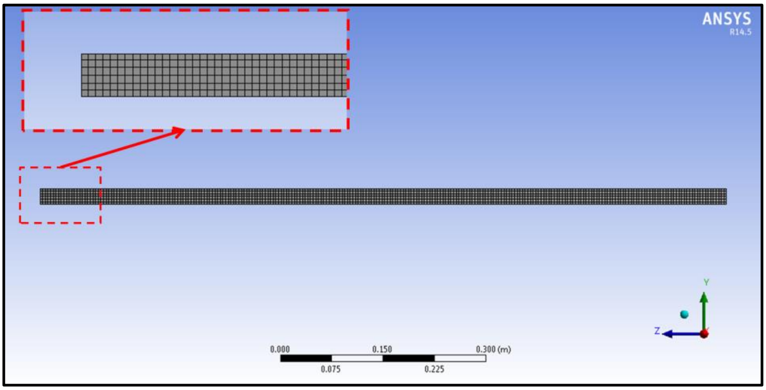
In total, there were four cases of simulation performed based on the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH which were equivalent to mass flow rate of 0.0561 kg/s, 0.1123 kg/s, 0.2245 kg/s and 0.4491 kg/s respectively. The inlet pressure was set as 4 bar (40000 Pa). The outlet pressure for each of the case was determined by the pressure drop obtained from Pressure Drop Online-Calculator [14]. The inlet and outlet pressure for each of the case is shown in Table 3.

Boundary conditions in CFD

The considered boundary conditions for the present study included inlet and outlet boundary of the liquid nitrogen, four cases of simulation based on inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. Prescribed pressure for inlet was set at 4 bar (40000 Pa) while the outlet was determined based on the pressure drop. For thermal boundary conditions, inlet and out temperatures were set as 77 K while the wall temperature set was 300 K as it was without thermal insulation. Process pipe material SS304 with thickness of 1.65mm and wall boundary conditions were used to bound fluid and solid regions. Boundaries direct motion of heat flow from fluid to the pipe wall, fluid (environments and liquid nitrogen) and solid regions (pipe) are represented by cell zones as shown in Figure 2, representing liquid nitrogen pipe flow model. Material and source terms are assigned to cell zones (solid zones and fluid zones), boundaries and internal surfaces were represented by face zones, while boundary data were assigned to face zones and axis boundaries (Figure 3).



(a) Isometric View



(b) Asymmetric Plane View

Figure 4: 3-D Half-Sectional Pipe Meshing

Figure 4 shows the computational mesh domain for the 3-D half-sectional pipe generated by ANSYS Meshing application.

Table 3: Pressure drop and outlet pressure

	Pressure drop(Pa)	**Outlet pressure (Pa)**
250 LPH	16	399984
500 LPH	53	399947
1000 LPH	181	399819
2000 LPH	628	399372

Result and Discussion

As shown in Figure 5 of the scaled residuals, the simulation solution achieved convergence in between 130 to 140 iterations. The temperature contours, velocity contours and pressure contours in isometric view and asymmetric plan view for the inlet volume flow rate of 250 LPH are shown in Figure 6 to 8 respectively. Liquid nitrogen flow is from z = 1 m (inlet) to z = 0 m (outlet), which is from left to right in the figures.

The temperature, velocity and pressure over the pipe length (z-coordinate) in wall line and asymmetric line for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH are shown in Figure 9 to 11 respectively. Liquid nitrogen flow is from z = 1 m (inlet) to z = 0 m (outlet), which is from left to right in Figure 6 to 8.

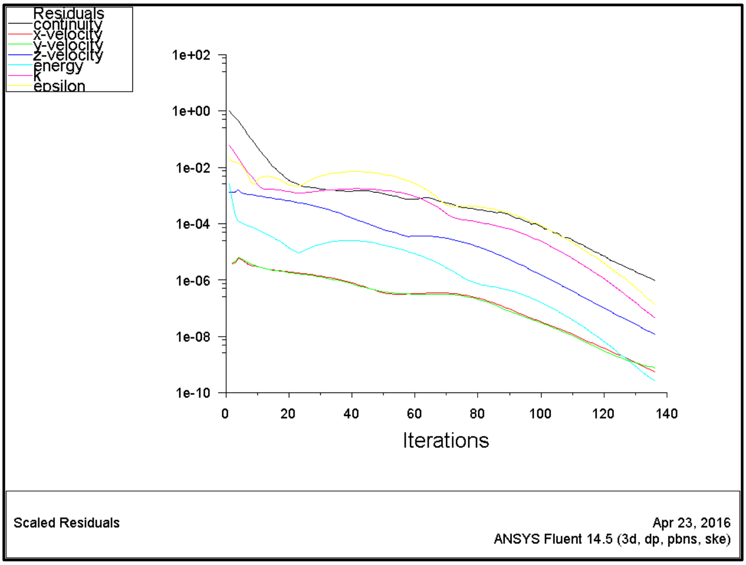
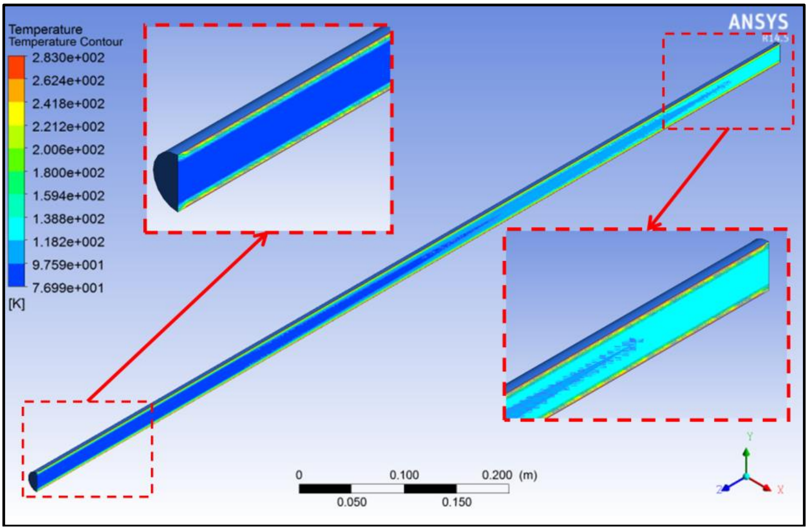
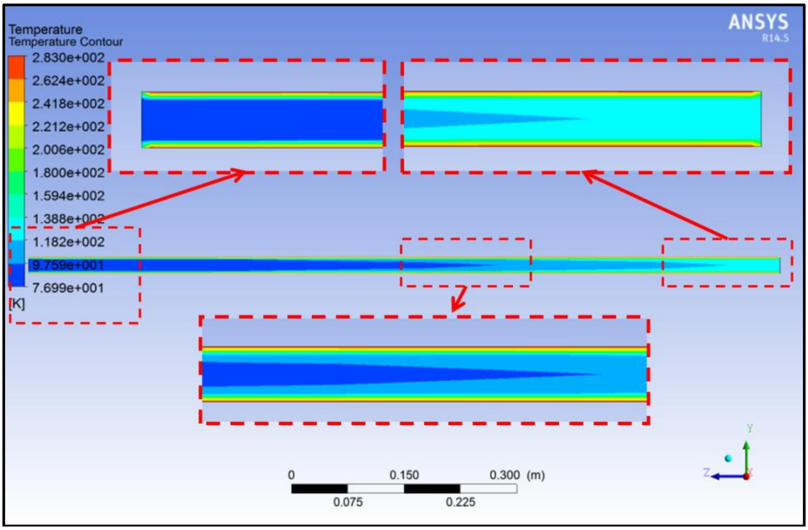


Figure 5: Scaled Residuals (250 LPH)



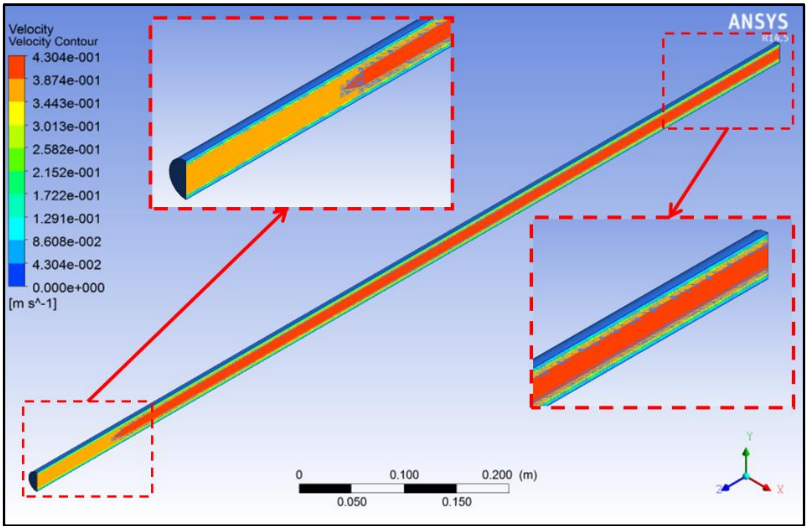
(a) Isometric View



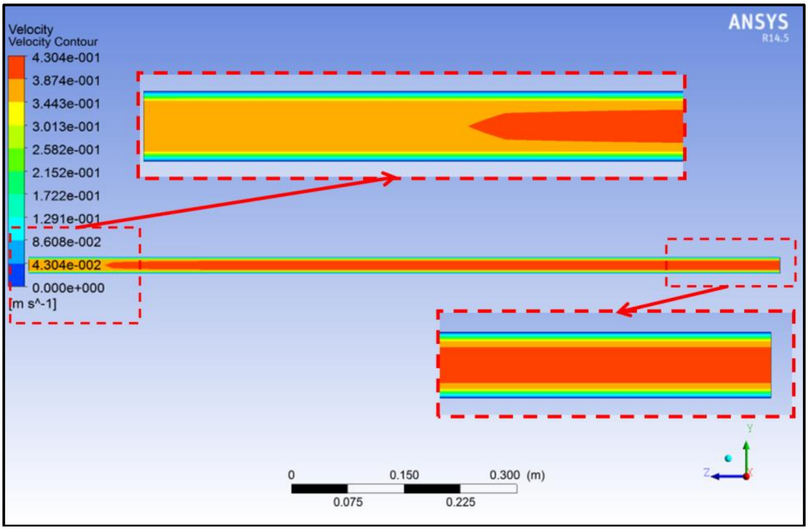
(b) Asymmetric Plane View

Figure 6: Temperature Contours Asymmetric Plane View (250 LPH)

As shown in Figure 6, the temperature is increasing along the flow (flow from left to right). The wall experienced high temperature as compared to the asymmetric line.



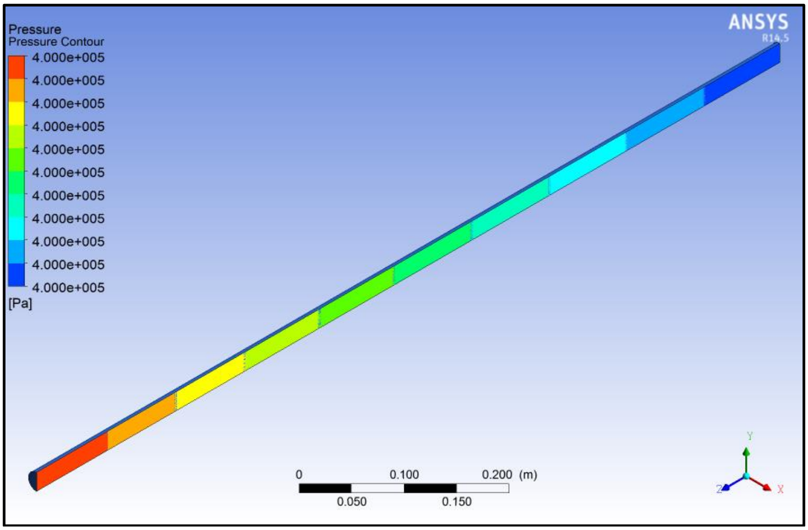
(a) Isometric View



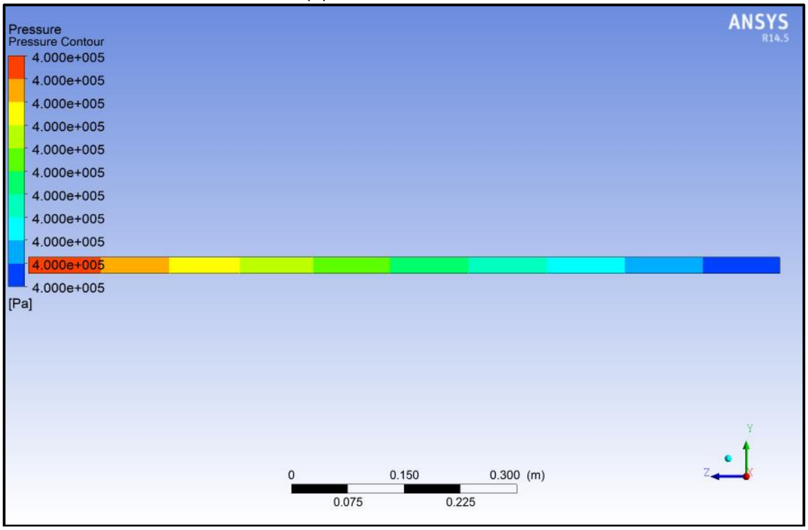
(b) Asymmetric Plane View

Figure 7: Velocity Contours Asymmetric Plane View (250 LPH)

As shown in Figure 7, the velocity increases before it reaches and maintains at the maximum along the flow (flow from left to right). The velocity at the wall is maintained at zero.



(a) Isometric View



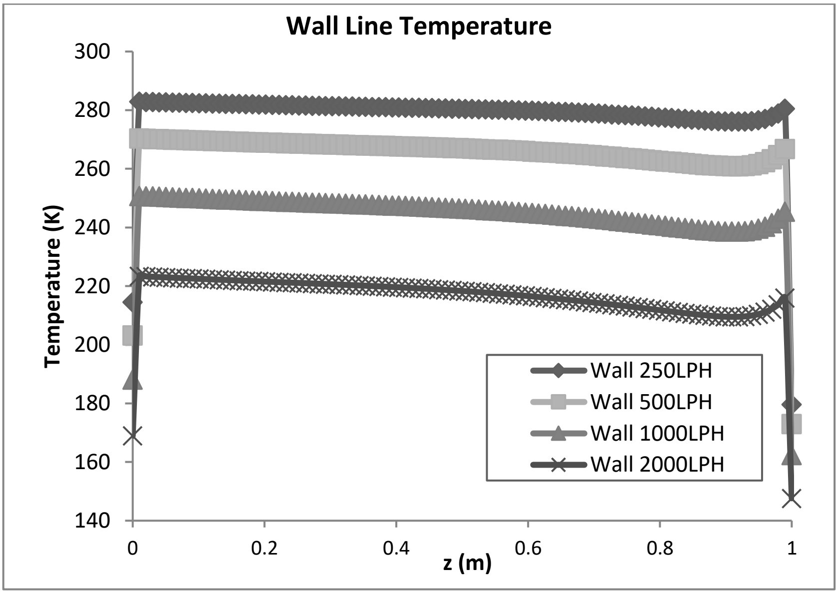
(b) Asymmetric Plane View

Figure 8: Pressure Contours Asymmetric Plane View (250 LPH)

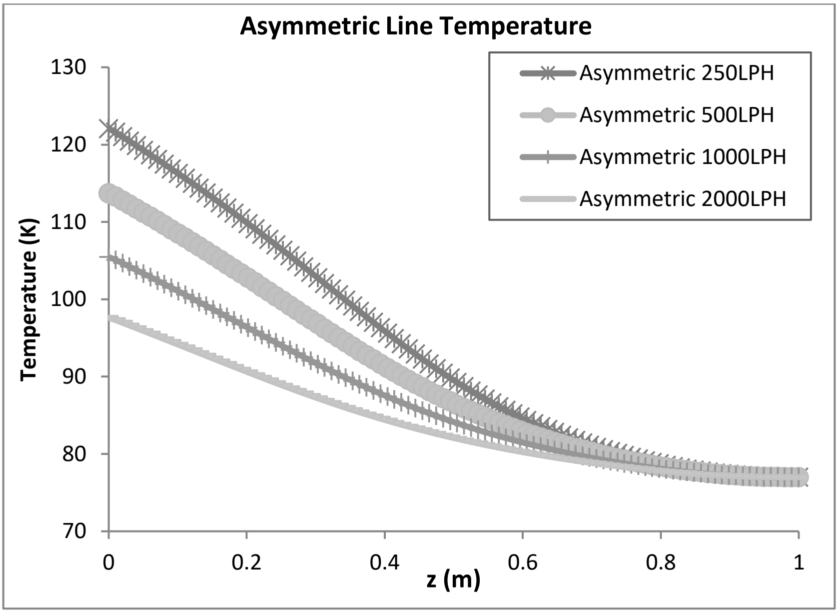
As shown in Figure 8, the pressure is decreasing along the flow (flow from left to right).

Temperature distribution

The temperature distribution over the pipe length (z-coordinate) in wall line and asymmetric line for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH is shown in Figure 9. The temperature is increasing along the flow (from inlet to outlet). The wall experienced high temperature as compared to the asymmetric line that deals with the wall exposed to the ambient. The rate of the temperature gradient decreases with the increase of the inlet volume flow rate. The maximum and minimum temperature at wall line and asymmetric line for the respective inlet volume flow rate is tabulated in Table 4.



(a) Wall Line Temperature; z = 1 m (inlet) to z = 0 m (outlet)



(b) Asymmetric Line Temperature; z = 1 m (inlet) to z = 0 m (outlet)

Figure 9: The Temperature over The Pipe Length (z-coordinate)

Table 4: Maximum and Minimum Temperature at Wall Line and Asymmetric Line

	250 LPH	**500 LPH**	**1000 LPH**	**2000 LPH**
Max. Wall Line Temp (K)	282.9	270.4	250.8	223.4
Min. Wall Line Temp (K)	179.6	173.0	162.4	147.6
$\triangle T_{wall\ line}$ (K)	103.3	97.4	88.4	75.8
Max. Asymmetric Line (K)	122.1	113.7	105.5	97.6
Min. Asymmetric Line (K)	77.0	77.0	77.0	77.0
$\triangle T_{asymmetric\ line}$ (K)	45.1	36.7	28.5	20.6

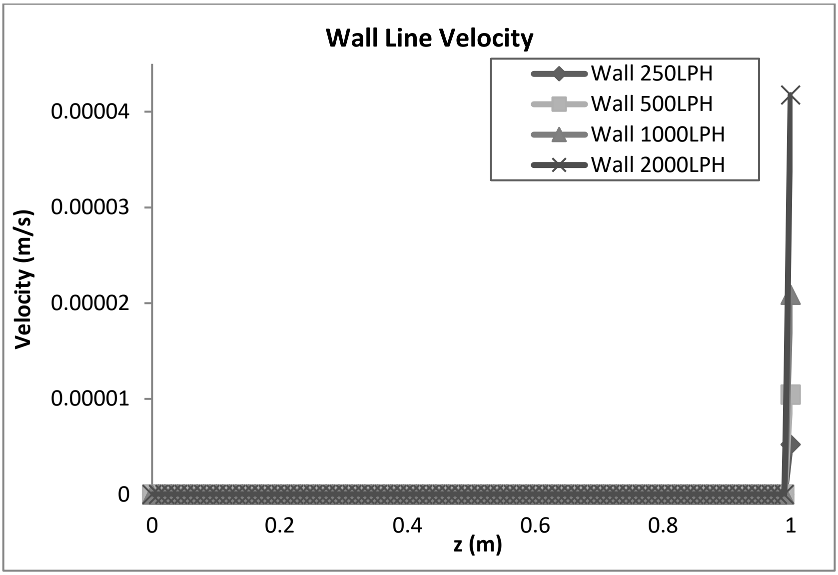
Table 4 shows the maximum and minimum temperature at wall line and asymmetric line of the pipe. As shown, the maximum wall line temperature is up to 282.3 K, 270.4 K, 250.8 K and 223.4 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The minimum wall line temperature was 179.6 K, 173.0 K, 162.4 K and 147.6 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The maximum wall line temperature occurred when the liquid nitrogen was near to the exit pipe outlet at z = 0.01 m. The minimum wall line temperature occurred when the liquid nitrogen enters pipe inlet at z = 1 m. The temperature differences at the wall line are 103.3 K, 97.4 K, 88.4 K and 75.8 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The maximum and minimum temperature at wall line is inversely proportional with the inlet volume flow rate. The rate of the temperature gradient is inversely proportional with the inlet volume flow rate. In order to maintain low temperature along the flow, higher inlet volume flow rate is required.

The maximum asymmetric line temperature was up to 122.1 K, 113.7 K, 105.5 K and 97.6 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The minimum asymmetric line temperature is 77 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH. The maximum asymmetric line temperature occurred when the liquid nitrogen exits pipe outlet at z = 0 m. The minimum asymmetric line temperature occurred when the liquid nitrogen enters pipe inlet at z = 1 m. The temperature differences at the asymmetric line are 45.1 K, 36.7 K, 28.5 K and 20.6 K for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The maximum temperature at asymmetric line is inversely proportional with the inlet volume flow rate.

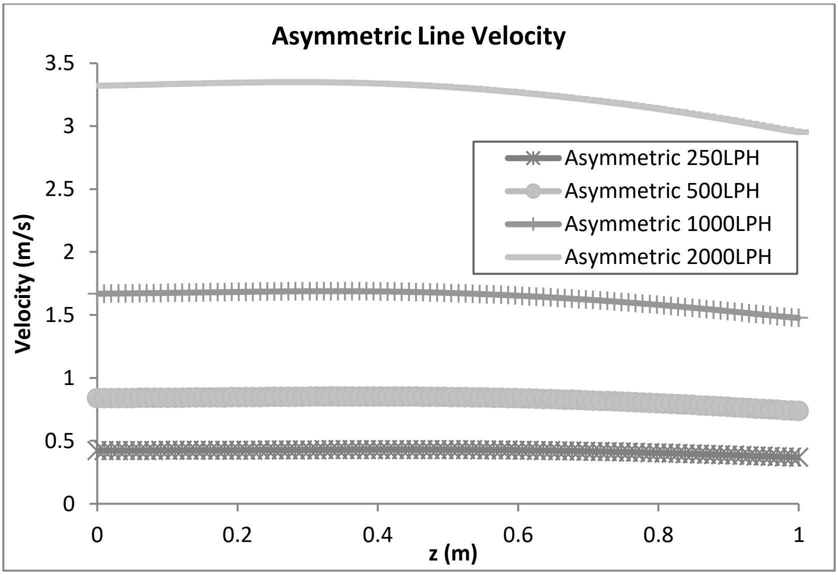
As a result from the simulation, the temperature distribution shows that the temperature of the flow exceeds the normal boiling point of liquid nitrogen (77.4 K) and this leads to the state changes from liquid to vapour and the flow becomes two phase flow. The two phase flow is more challenging to analyse.

Velocity distribution

The velocity distribution over the pipe length (z-coordinate) in wall line and asymmetric line for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH is shown in Figure 10. The wall line velocity dropped to zero near the inlet. The asymmetric line velocity is increasing along the flow (from inlet to outlet). The rate of velocity gradient at the asymmetric line is increasing with the increase of the inlet volume flow rate. The maximum and minimum velocity at wall line and asymmetric line for the respective inlet volume flow rate is tabulated in Table 5.



(a) Wall Line Velocity; z = 1 m (inlet) to z = 0 m (outlet)



(b) Asymmetric Line Velocity; z = 1 m (inlet) to z = 0 m (outlet)

Figure 10: The Velocity over The Pipe Length (z-coordinate)

Table 5: Maximum and Minimum Velocity in Wall Line and Asymmetric Line

	250 LPH	**500 LPH**	**1000 LPH**	**2000 LPH**
Max. Wall Line velocity (m/s)	0.01×10^{-3}	0.01×10^{-3}	0.02×10^{-3}	0.04×10^{-3}
Min. Wall Line velocity (m/s)	0	0	0	0
$\triangle\ v_{wall\ line}$ **(m/s)**	0.01×10^{-3}	0.01×10^{-3}	0.02×10^{-3}	0.04×10^{-3}
Max. Asymmetric velocity (m/s)	0.43	0.85	1.69	3.35
Min. Asymmetric velocity (m/s)	0.37	0.74	1.48	2.95
$\triangle\ v_{asymmetric\ line}$ **(m/s)**	0.06	0.11	0.21	0.40

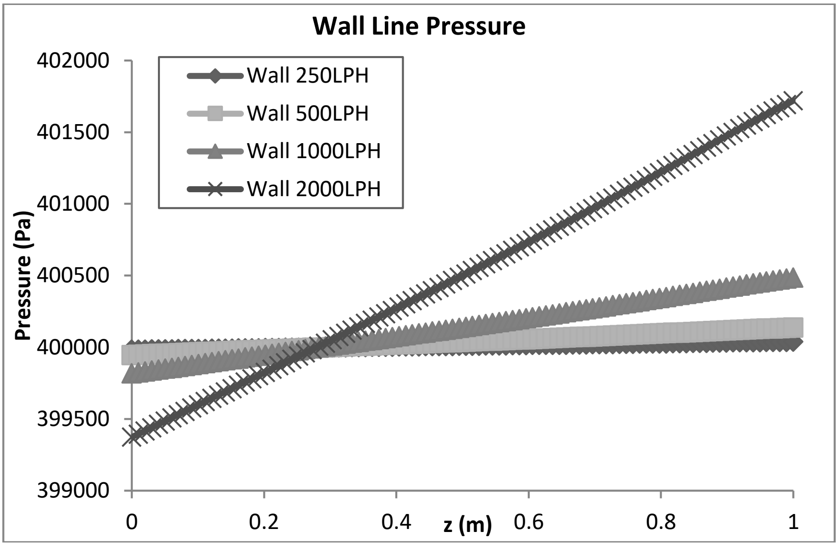
Table 5 shows the maximum and minimum velocity. As shown, the wall line velocity is nearly to zero regardless of the inlet volume flow rate. This is the indication of obeying the pipe flow principle.

The maximum asymmetric line velocity was up to 0.43 m/s, 0.85 m/s, 1.69 m/s and 3.35 m/s for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The minimum asymmetric line temperature is 0.37 m/s, 0.74 m/s, 1.48 m/s and 2.95 m/s for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH. The maximum asymmetric line velocity occurred at z = 0.43 m, z = 0.38 m, z = 0.33 m and z = 0.28 m for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The minimum asymmetric line velocity occurred when the liquid nitrogen enters pipe inlet at z = 1 m. The velocity differences at the asymmetric line are 0.06 m/s, 0.11 m/s, 0.21 m/s and 0.40 m/s for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The velocity at asymmetric line is directly proportional with the inlet volume flow rate.

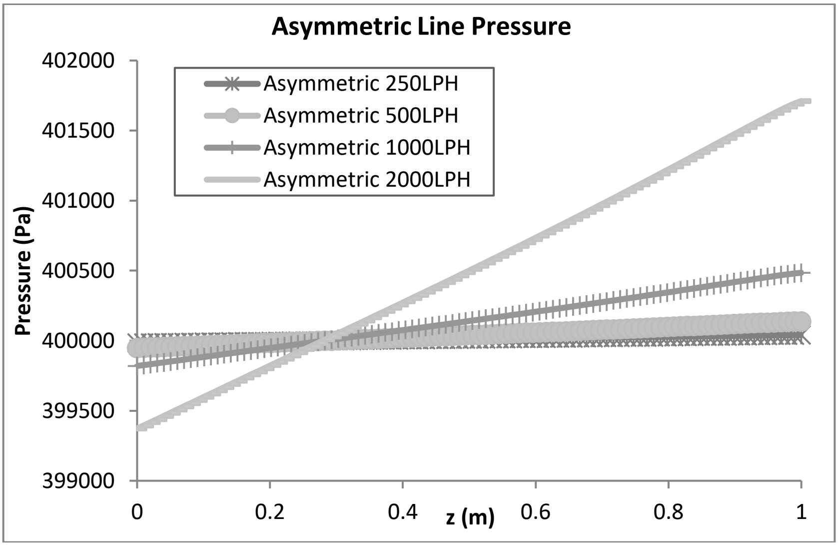
From the simulation results obtained, in order to have the flow velocity of less than 1 m/s for the process pipe with 22.1 mm inner diameter and 1 m length, the inlet volume flow rate should not be more than 500 LPH.

Pressure distribution

The pressure distribution over the pipe length (z-coordinate) in wall line and asymmetric line for the in inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH is shown in Figure 11. The pressure decreases along the flow at the wall line and asymmetric line (from inlet to outlet). The rate of pressure gradient is increasing with the increase of the inlet volume flow rate. The maximum and minimum pressure at wall line and asymmetric line for the respective inlet volume flow rate is tabulated in Table 6.



(a) Wall Line Pressure; z = 1 m (inlet) to z = 0 m (outlet)



(b) Asymmetric Line Pressure; z = 1 m (inlet) to z = 0 m (outlet)

Figure 11: The Pressure over The Pipe Length (z-coordinate)

Table 6: Maximum and Minimum Pressure in Wall Line and Asymmetric Line

	250 LPH	**500 LPH**	**1000 LPH**	**2000 LPH**
Max. Wall Line Pressure (Pa)	400040	400139	400487	401720
Min. Wall Line Pressure (Pa)	399984	399947	399820	399375
$\triangle \boldsymbol{P_{wall\ line}}$ **(Pa)**	56	192	667	2345
Max. Asymmetric Pressure (Pa)	400040	400138	400485	401711
Min. Asymmetric Pressure (Pa)	399984	399947	399820	399374
$\triangle \boldsymbol{P_{asymmetric\ line}}$ **(Pa)**	56	191	665	2337

Table 6 shows the maximum and minimum pressure. As shown, the maximum wall line pressure is up to 400040 Pa, 400139 Pa, 400487 Pa and 401720 Pa for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The minimum wall line pressure is 399984 Pa, 399947 Pa, 399820 Pa and 399375 Pa for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The maximum wall line pressure occurred when the liquid nitrogen enters pipe inlet at z = 1 m. The minimum wall line pressure occurred when the liquid nitrogen exits pipe outlet at z = 0. The pressure differences at the wall line are 56 Pa, 192 Pa, 667 Pa and 2345 Pa for the inlet volume flow rate of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH respectively. The maximum and minimum pressure at wall line is directly proportional with the inlet volume flow rate. The pressure change is another key factor to maintain the liquid nitrogen as fluid state along the pipe flow.

Conclusion

The liquid nitrogen pipe flow was successfully simulated in four different inlet volume flow rates of 250 LPH, 500 LPH, 1000 LPH and 2000 LPH in the present study. The turbulent liquid nitrogen pipe flow was obtained from the simulation.

The temperature increased along the flow and the wall experienced a higher temperature compared to asymmetric line. The maximum and minimum temperature at wall line was inversely proportional with the inlet volume flow rate. The rate of the temperature gradient was inversely proportional with the inlet volume flow rate. In order to maintain low temperature along the flow, higher inlet volume flow rate is required. Temperature distributions obtained from simulations showed the temperature of the flow exceeded the normal boiling point of liquid nitrogen (77.347 K) and this led to the state changes from liquid to vapour and the flow became two phase flow. The two phase flow is more challenging to analyse.

The velocity at asymmetric line is directly proportional with the inlet volume flow rate. In order to have the flow velocity of less than 1 m/s for the process pipe with 22.1 mm inner diameter and 1 m length, the inlet volume flow rate should not be more than 500 LPH as per simulation results.

The maximum and minimum pressure at wall line is directly proportional with the inlet volume flow rate. The pressure change is another key factor to maintain the liquid nitrogen as fluid state along the pipe flow.

The liquid nitrogen pipe flow as turbulent flow was simulated and the flow velocity and the temperature distribution were obtained. The results in the present study can be a reference for the simulation studies of liquid nitrogen pipe flow with thermal insulation system, as well as other cryogens pipe flow.

Acknowledgement

I am grateful to the industry partner Cryogas Tech, which has been helpful and generous with their knowledge on cryogenics.

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