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# Experimental Investigation of Double Pipe Heat Exchangers for Cryogenic Applications

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***Abstract*** **-** This study aims to directly recover cold energy from liquid nitrogen evaporation for cooling applications utilizing a double-pipe heat exchanger. The double-pipe heat exchanger has an inner tube inner diameter of 10.7mm, an inner tube outer diameter, an outer tube inner diameter of 20mm, and an outer tube outer diameter of 24mm. Experiments were carried out with saturated liquid nitrogen with an inlet temperature of 93 K and mass flux of 66, 144, and 238 kg/s-m$^2$ flowing at the tube side while simultaneously being heated by a heat transfer fluid (HTF) at the annular side of the heat exchanger. Ethylene glycol-water mixture (35% wt.) with inlet temperatures ranging from 295 to 300 K and flow rates ranging from 0.03 to 0.22 kg/s. The annulus side of the double-pipe heat exchanger was split into three sections to avoid severe ice accumulation due to the inevitable decrease in the HTF temperature as the HTF flows along. The results show that the outer surface heat flux of the inner tube increases substantially with the increase of liquid nitrogen flow rate, which suggests that the flowing nitrogen is in the film boiling region. Furthermore, experimental results show the feasibility of utilizing film boiling for liquid nitrogen cold energy recovery. The vapor blanket formed at the wall surface prevents the wall temperature from overcooling while recovering large amounts of cold energy due to the immense temperature difference between the HTF and nitrogen.
***Keywords*****:** Flow boiling; Liquid nitrogen; Film boiling; Cryogenic cooling; Cold energy recovery

## 1. Introduction

Nitrogen is a transparent, odorless, and non-toxic inert gas with low surface tensions hence is desirable for a variety of industrial processes such as food packaging, chemical bracketing, and electronics assembling. In addition, nitrogen is also an abundant substance that constitutes approximately 78% of the earth's atmosphere. The development of cryogenic separation [1], pressure-swing absorption [2], and polymeric membrane [3] techniques enable nitrogen to be produced at a commercial scale with high purity. However, due to low densities, nitrogen is usually stored and transported in liquid form or highly pressurized gas form, where conditions are often too extreme for direct usage. A popular approach for liquid nitrogen (LN2) is to evaporate the LN2 to Gas nitrogen with moderate temperature and pressure utilizing an evaporator. As a result of the change of phase and significant temperature variations during the evaporation process, a large amount of heat can be absorbed by nitrogen as both sensible and latent heat leading to various research [4].

The application of cooling utilizing cryogens has been in the interest of many industries. For example, Skobel and Davey [5] designed a liquid nitrogen-cooled beverage dispenser. In his design, beverages are cooled rapidly by liquid nitrogen through a shell and coil heat exchanger. Beverages in the disperser are cooled to a desired viscosity or percentage of frozen by controlling the liquid nitrogen flow rate of the coil twined to the disperser. The design can provide fast and efficient cooling without electricity, making it suitable for operating in remote areas. The cooling ability of cryogens can also be applied to air conditioning systems. In 1960, Harold [6] designed a cryogen-cooled (liquid air/ \Liquid oxygen) air conditioning system, where liquid air/oxygen flow at the coiled tube side of the shell-and-tube heat exchanger is vaporized and superheated by incoming hot ambient air through the shell side. The system has a relatively simple configuration with no moving parts making it lightweight and suitable for space applications.

Understanding the heat transfer mechanism of liquid nitrogen during flow boiling is crucial for designing and implementing liquid nitrogen for cooling. However, some studies [7-9] suggest that there is a discrepancy in the heat transfer and flow characteristics between liquid nitrogen and other conventional fluids. Moreover, experiments regarding the flow boiling of liquid nitrogen are difficult and costly to carry out due to the fact that it requires operating in extreme conditions, such as at cryogenics temperatures (<120K) and high pressure. Therefore, this study utilizes a simple design, a double-pipe heat exchanger, to experimentally investigates the heat transfer mechanism of liquid nitrogen evaporation while being fluid-heated.

Double-pipe heat exchangers are commonly used in various industries. They have several advantages that could potentially be suitable for cryogenic cooling. First, it is simple in configuration, consisting of only two concentric pipes with different diameters, requiring less construction effort, and has a relatively simple heat transfer mechanism. Secondly, there are many articles available regarding the heat transfer of flow boiling in a straight tube and liquid flowing on the annular side of the tube. Last but not least, the cooling capacity of the heat exchanger can easily be increased by simply adding more double-pipe tubes in parallel. Hence, it may enable less discrepancy in heat transfer performance when scaled to larger heat load capacity applications.

## 2. Experimental Setup and Data Reduction

Figure 1 and Figure 2 show the flow schematic and the sectional view of the double-pipe heat exchanger for the current study, respectively. Nitrogen flows inside the inner tube, while the ethylene glycol-water mixture flows through the annular space in the opposite direction. The schematic diagram of the system is presented in Figure 3. Liquid nitrogen is first forced out of the tank by applying pressure and runs through the tube side of three counter-flow double-pipe heat exchangers. To ensure pure vapor nitrogen entering the gas flow meter installed at the end of the nitrogen pipe line, an additional heat exchanger is installed at the exit of the test section. The liquid nitrogen in the test sections is heated up by hot HTF flowing through the annulus side of the double-pipe heat exchanger. To avoid severe ice accumulation of the HTF due to the continuous decrease of the local bulk temperature along the tube and also to account for the varying flow conditions of nitrogen, the test section is separated into three parts.

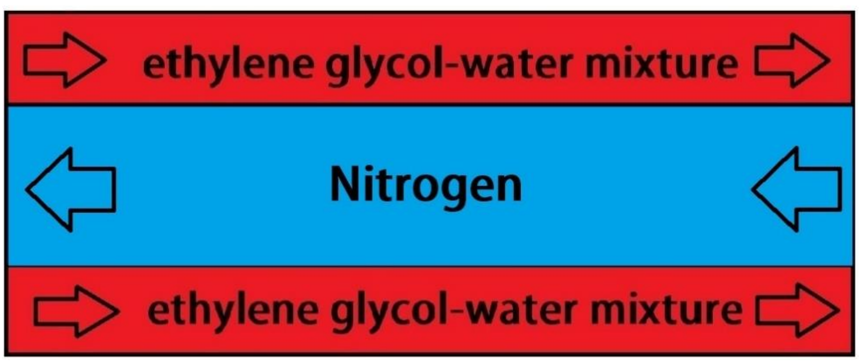


Figure 1: Flow schematic of the double-pipe heat exchanger

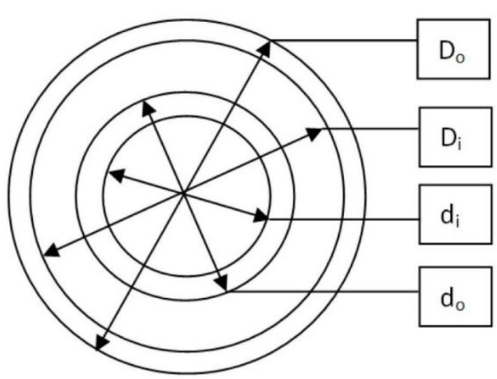


Figure 2: Sectional view of the double-pipe heat exchanger

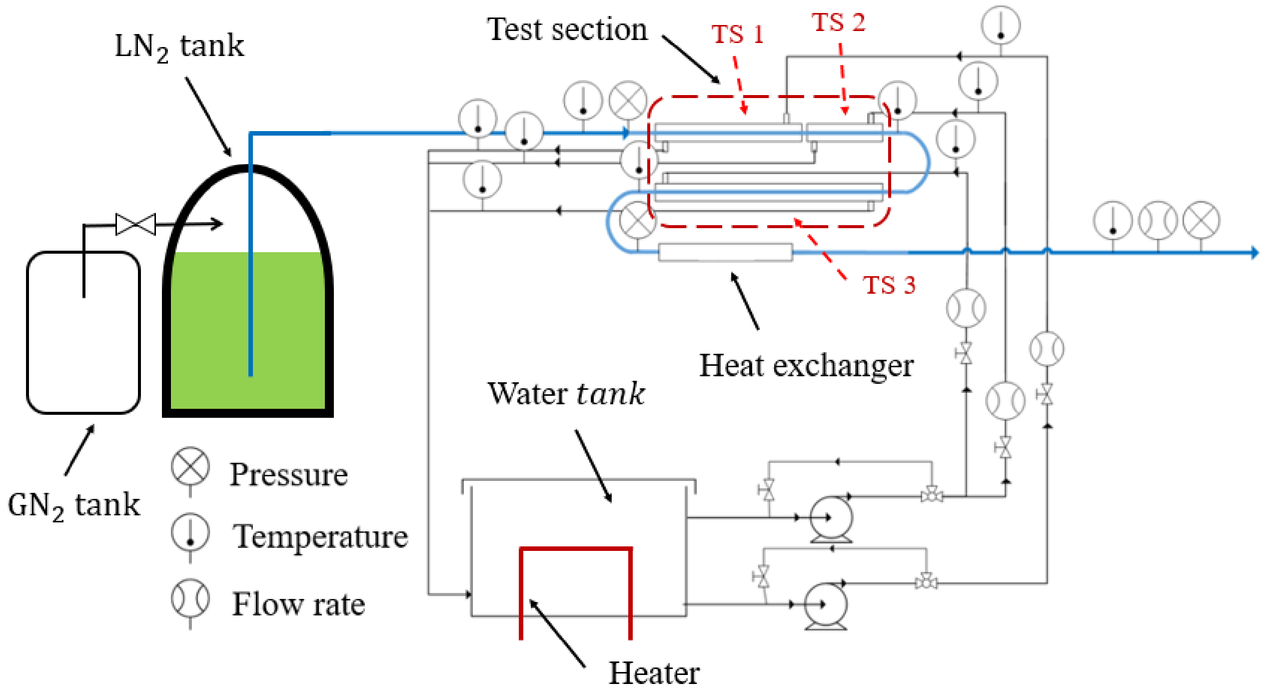


Figure 3: Schematic diagram of the system

The inner tube of the double pipe exchanger is a smooth stainless steel (SUS 304) tube with an outer diameter of 12.7mm and a uniform thickness of 1mm. T-type thermal couples are installed at the top, side, and bottom of the inner tube with a horizontal spacing of 100mm, shown in figure 4. The outer tube of the double pipe heat exchanger is a 2mm thick PVC tube with an outer diameter of 24mm. Transparent tubes are chosen to determine the ice formation of the HTF at the annuls side of the heat exchanger. Moreover, the effective heat exchanger length (L) and other characteristic dimensions of the test section are listed in table 1.

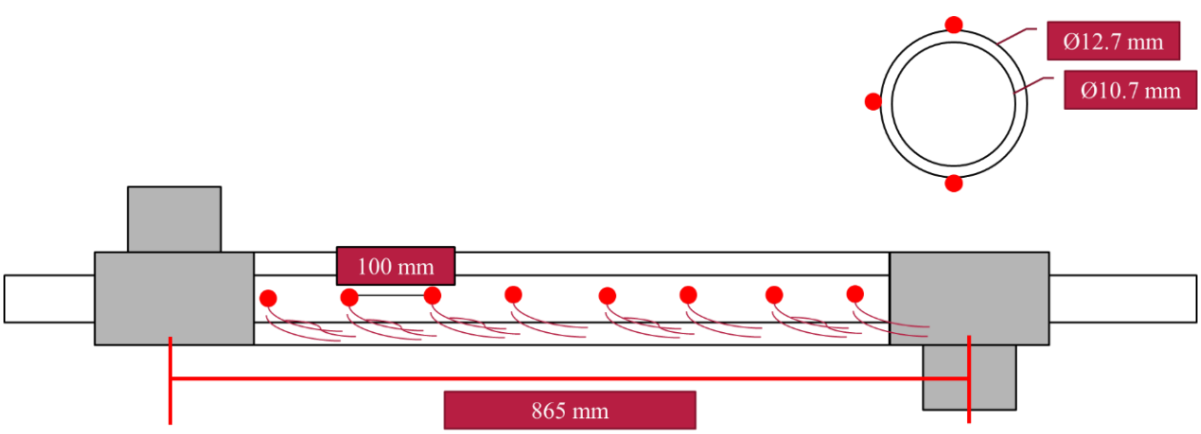


Figure 4: Diagram of test section (TS 1) 1

Table 1: Characteristic dimensions of the test sections

| | TS 1 | TS 2 | TS 3 |
|---|---|---|---|
| L (mm) | 865 | 350 | 1450 |
| $d_i$ (mm) | 10.7 | | |
| $d_o$ (mm) | 12.7 | | |
| $D_i$ (mm) | 20 | | |
| $D_o$ (mm) | 24 | | |

The test parameters of the double-pipe experiments are listed below (Table 2). Low-temperature nitrogen runs through the tube side while being heated by hot HTF (Water and ethylene glycol mixture) flowing at the annulus side. The inlet conditions of nitrogen and HTF are varied to find the ideal combination.

Table 2: Operating conditions

| Working fluid | Nitrogen | HTF |
|---|---|---|
| Section | Tube-side | Annular-side |
| Inlet state | Saturated liquid | Water and ethylene glycol mixture (50% wt.) |
| Inlet temperature (°C) | -172~-166 | 26~23 |
| Mass flow rate (kg/s) | 0.007 ~ 0.025 | 0.03 ~ 0.22 |

The total heat transfer (Q) of the HTF during cooling can be calculated by the energy balance equation shown as equation 1; while the heat transfer coefficient of the outer surface of the inner tube ($h_i$) can obtained by equation 2.

$$Q_{HTF} = \dot{m}C_p\left(T_{HTF,in} - T_{HTF,out}\right) \tag{1}$$

$$h_i = \frac{Q_{HTF}}{A_o(T_{bulk} - T_w)} \tag{2}$$

where:

$$T_{bulk} = (T_{LN2,in} + T_{LN2,out})/2 \tag{3}$$

## 3. Results and Discussion

This section presents and discusses the cooling capacity of each double-pipe test section under different nitrogen and HTF inlet condition. The cooling capacity is determined by the energy conservation of the HTF fluid at the annulus side (equation 1). For all experiments, the HTF first runs through the annulus side for a few minutes before gradually opening the liquid nitrogen valve to reach the desired flow rate. Once steady state conditions are met, data are recorded once per second for 5 minutes. The cooling capacity is divided by the heat transfer area to neglect the effects of the test tube length.

Figure 5 to 7 shows the experimental data of the wall heat flux obtained for each section under various inlet conditions. It is apparent that the heat flux increases significantly with the mass velocity of liquid nitrogen ($G_{N2,in}$). The heat flux for all test sections increases over two times as $G_{N2,in}$ increases from 66 to 238 kg/s-m$^2$. Moreover, test section 3 surprisingly has a higher heat flux than other sections. A possible explanation is that liquid nitrogen is in the film boiling region while operating in the first two sections. Although all heat flux is at least 10kW under their respective CHF, since the nitrogen tube is heated first by the HTF, nitrogen may have stayed in the film boiling region due to continuous heating. If boiling occurs in the film boiling region, the heat transfer coefficient at the tube side would be smaller than the annulus side. This can account for why increasing $G_{N2,in}$ has such a significant effect on the wall heat flux. Additionally, other factors, such as the inlet temperature and the mass flow rate of the HTF, are shown to have minimal effects on the heat flux. Nevertheless, only limited factors under a limited range are tested.

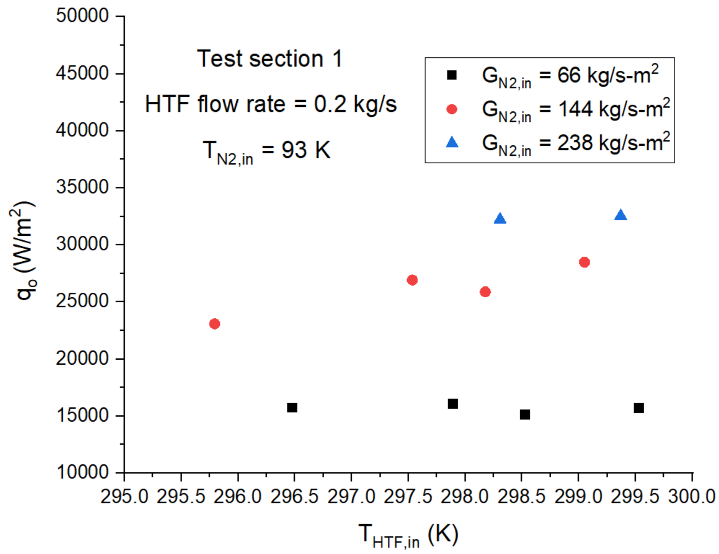


Figure 5: Annulus side wall heat fluxes at test section 1

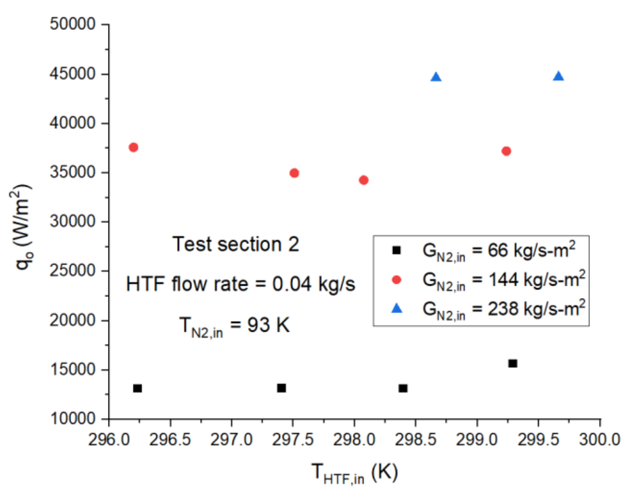


Figure 6: Annulus side wall heat fluxes at test section 2

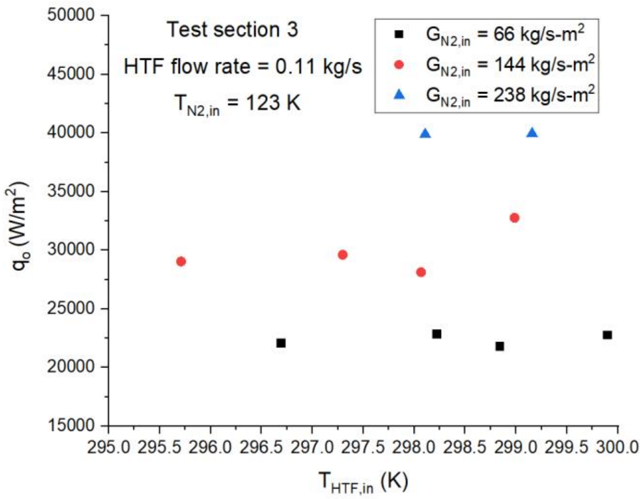


Figure 7: Annulus side wall heat fluxes at test section 3

Figure 8 to 10 shows the estimations of the heat transfer coefficient of flowing nitrogen in the horizontal test sections during operation. It is apparent that the heat transfer coefficient is too lower to be in the nucleate boiling region. Hence, it is reasonable to assume that nitrogen is either in the film boiling region or the single vapor phase region for all cases tested. Furthermore, the heat transfer coefficient shows a similar trend as the wall heat flux, which increase significantly with the increase in nitrogen flow rate.

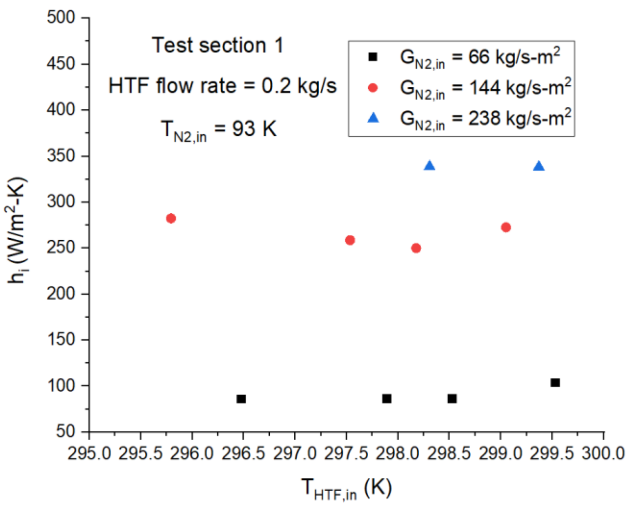


Figure 8: Tube side wall heat fluxes at test section 1

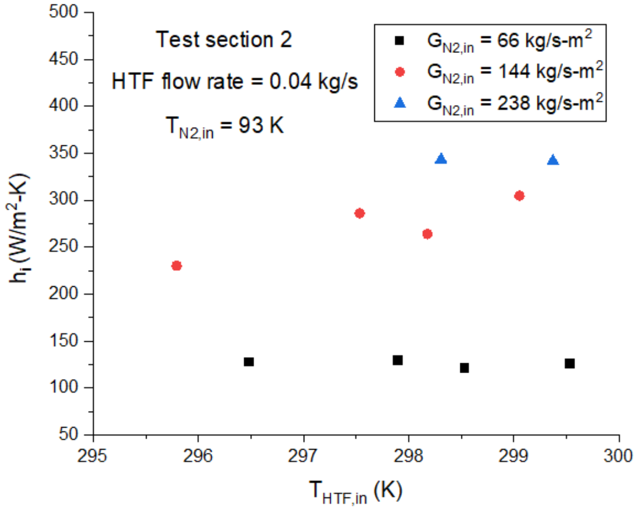

Figure 9: Tube side wall heat fluxes at test section 2

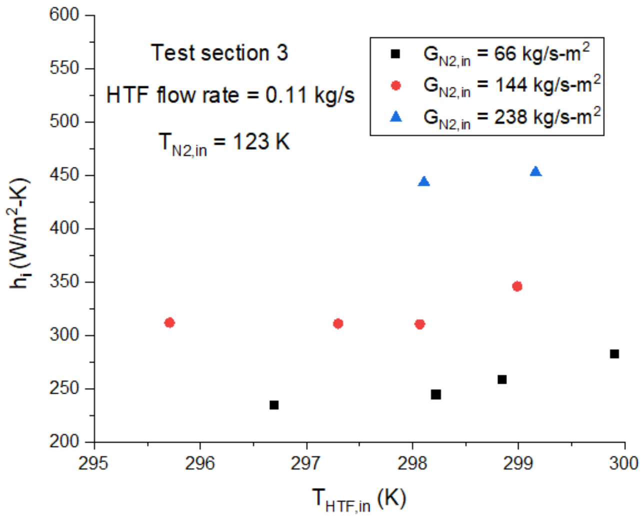

Figure 10: Tube side wall heat fluxes at test section 3

## 4. Conclusion

This study experimentally investigates the cooling performance of double-pipe heat exchangers under cryogenic conditions. The inner tubes of the heat exchanger are made of smooth stainless steel with an outer diameter of 12.7mm and a tube thickness of 10mm. The outer tubes are transparent PCV tubes with an inner diameter of 20mm and an outer diameter of 24mm. Saturated liquid nitrogen with an inlet temperature of 93 K and mass flux of 66, 144, and 238 kg/s-m$^2$ flows inside the inner tube while being heated by an Ethylene glycol-water mixture (35% wt.) flowing at the annular side with inlet temperatures ranging from 295 to 300 K and flow rates ranging from 0.03 to 0.22 kg/s. Within the aforementioned conditions the main findings are listed below:

1. Both the surface heat flux and the heat transfer coefficient of the outer surface of the inner tube increase significantly with the increase in LN2 inlet flow rate.
2. The effect of tube position and the inlet temperature of the HTF does not affect the overall heat transfer noticeably; however, only a limited range of HTF inlet temperatures are tested.

3. If the heat transfer fluid heats the inner tube of the double-pipe heat exchanger prior to operation, film boiling can be consistently maintained with a heat flux far below the critical heat flux.
4. Visible ice formations on the HTF side are only observed at the annulus side of the longest test section when the flow rate and inlet temperature of the HTF are dropped intentionally.

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## References

[1] C. Linde, “Process of Producing Low Temperatures, the Liquefaction of Gases, and the Separation of the Constituents of Gaseous Mixtures and the Separation of the Constituents of Gaseous Mixtures,” 727, 650, May 12, 1903.
[2] A. Schulte-Schulze-Berndt and K. Krabiell, “Nitrogen generation by pressure swing adsorption based on carbon molecular sieves,” *Gas Separation & Purification*, vol. 7, no. 4, pp. 253–257, 1993.
[3] W. J. Koros and R. Mahajan, “Pushing the limits on possibilities for large scale gas separation: which strategies?,” *J. Membr. Sci.*, vol. 175, pp. 181–196, 2000.
[4] Y. Yildiz and Muammer. Nalbant, “A review of cryogenic cooling in machining processes,” *Int J Mach Tools Manuf*, vol. 48, pp. 947–964, 2008.
[5] R. M. Skobel and D. Davey, “Liquid nitrogen cooled beverage dispenser,” US20080289357A1, May 20, 2008.
[6] R. Harold, “Air conditioning system,” 1960.
[7] V. V. Klimenko and A. M. Sudarchikov, “Investigation of forced flow boiling of nitrogen in a long vertical tube Investigation of forced flow boiling of nitrogen in a long vertical tube,” *Cryogenics (Guildf)*, vol. 23, no. 7, pp. 379–385, 1983.
[8] R. Yun, J. S. Hwang, J. T. Chung, and Y. Kim, “Flow boiling heat transfer characteristics of nitrogen in plain and wire coil inserted tubes,” *Int J Heat Mass Transf*, vol. 50, no. 11, pp. 2339–2345, 2007.
[9] P. Zhang and X. Fu, “Two-phase flow characteristics of liquid nitrogen in vertically upward 0.5 and 1.0 mm micro-tubes: Visualization studies,” *Cryogenics (Guildf)*, vol. 49, no. 10, pp. 565–575, 2009.