DESIGN OF A CRYOPRESERVATION CHAMBER USING MIXED REFRIGERANT JOULE-THOMSON CRYOCOOLER TECHNOLOGY

A. Markan[1], P.M. Ardhapurkar[1,2], M.D. Atrey[1]

[1]*Mechanical Engineering Department, IIT Bombay, Powai, Mumbai – 400 076*
[2]*S.S.G.M. College of Engineering, Shegaon – 444 203*

The process of cryopreservation involves the cooling of biological materials to a temperature in the range of 100 – 150 K in an insulated chamber. The Mixed Refrigerant Joule-Thomson (MRJT) cryocooler technology, which is the focus of the present study, could be employed to cool the cryopreservation chamber. The MRJT cryocooler uses a multi-component mixture of nitrogen-hydrocarbons as the working fluid. The design of the cryopreservation chamber involves compressor selection with appropriate oil filter mechanism, MRJT cryocooler design and design of vacuum chamber and cryogenic chamber.

The heat exchanger design is a core aspect of the cryopreservation chamber design. A tube-in-tube helically coiled heat exchanger is analyzed numerically to get an optimal design for the heat exchanger. Recently published correlations have been applied to estimate the boiling and condensation heat transfer coefficients. The predicted heat transfer coefficients are utilized by the algorithm to determine the temperature profile along the heat exchanger which is then used to compute the optimal design parameters of the heat exchanger. The estimated parameters are compared with the prevailing experimental data to elucidate the applicability of the model. After validation, the algorithm is used to design the heat exchanger for the cryopreservation chamber.

Key words: Cryopreservation Chamber, Mixed Refrigerant Joule-Thomson (MRJT) Cryocooler, Tube-in-Tube Helically Coiled Heat Exchanger, Numerical Model

INTRODUCTION

The Joule-Thomson (JT) or the Linde Hampson cryocoolers are used for various space, military and medicinal applications. The technology has been preferred over other cryocoolers due to their compactness, cool-down characteristics, lack of moving parts at the cold end and a vibration free cooling ability. Many researchers [1,2] have suggested the use of a refrigerant mixture of nitrogen-hydrocarbons as the working fluid in a Mixed Refrigerant Joule-Thomson (MRJT) cryocooler. It has been illustrated that the use of such mixtures reduces the high pressure in the cryocooler and increases the effectiveness of the heat exchanger [1]. This permits the use of oil-lubricated compressors making the use of MRJT cryocoolers economically viable.

The cryopreservation chamber ensures cooling of the biological materials to a very low temperature. The biological materials that are required to be preserved at cryogenic temperatures include adult stem cells, umbilical cord blood stem cells, special blood cells, organ tissue, plant seeds, etc. Traditionally liquid nitrogen has been used for cryopreservation. However, storage in liquid phase of liquid nitrogen could drag infectious particles such as viruses among the samples [3]. Berz et al. [4] deliberated the possibility of using mechanical refrigerators instead of liquid nitrogen storage. The use of a MRJT cryocooler, driven by an oil-lubricated commercial compressor with moderate delivery pressure, would represent an economically viable option to cool the cryopreservation chamber.

Cryopreservation chamber prototypes have been developed by Gong [5,6], Panasonic [7] and Thermo Scientific [8]. Gong tested two such chamber prototypes for different temperature ranges. One was based on a dual MRJT cycle operating at a temperature of about 87 K [5] using a twin model reciprocating compressor. The other was based on a single stage MRJT cycle operating at a temperature of about 120 K [6] utilizing a single stage hermitic air conditioning compressor. In both the cases, the compressor had an input power of about 2-3 kW. Gong [5] also illustrated that a refrigeration effect about 20 W is necessary for chamber volume of 80 L.

The present study aims to design a cryopreservation chamber using MRJT technology to provide a refrigeration temperature of about 120 K. As evident, the MRJT cryocooler is the most important component of this chamber. The other components such as compressor, after-cooler, oil filters etc. are commercially available and they need to be selected according to the working pressure and temperature requirements. However, the heat exchanger, vacuum chamber, cryogenic chamber and cold end heat exchanger need to be designed and fabricated carefully. The current study focuses mainly on the design of the heat exchanger in the MRJT cryocooler.

HEAT EXCHANGER DESIGN

The MRJT cryocooler employs a multi-component mixture as the working fluid which undergoes condensation and boiling heat transfer simultaneously during circulation through the heat exchanger. A high temperature glide in the heat exchanger leads to a significant variation in the thermo-physical properties of the working fluid at cryogenic conditions [2]. It is imperative to numerically analyze the heat exchanger. The design parameters for the heat exchanger need to be decided beforehand so as to minimize the losses occurring during the heat exchange. A tube-in-tube helically coiled counter-flow heat exchanger is numerically investigated for this purpose.

NUMERICAL MODEL

A numerical model is developed for the tube-in-tube heat exchanger which consists of one or more inner tubes arranged inside the outer tube and oriented in a helical coil arrangement. The hot fluid flows through the inner tube(s) at high pressure while the cold fluid flows through the annular region at low pressure. As the working fluid is a multi-component two phase mixture, the changes in the properties are significant from the ambient temperature to cryogenic temperatures. Hence, having knowledge about the actual temperature distribution along the heat exchanger length would provide a better understanding of the cryocooler performance. An attempt to integrate a standard temperature sensor like the resistance temperature detector (e.g. PT 100) may affect the performance of the helically coiled heat exchanger as the flow might be obstructed [9]. This brings to the fore a need to numerically predict the temperature profile along the length of the heat exchanger to comprehend its behaviour.

The following assumptions are made to formulate the numerical model for the heat exchanger:

- The flow through the heat exchanger is steady and one-dimensional.
- Pressure is assumed to be constant for the hot and cold fluid respectively.

- The thermo-physical properties of the working fluid vary with the temperature in the axial direction.
- No heat in leak from the surroundings to the heat exchanger.
- The axial heat conduction through the heat exchanger material and the working fluid is neglected.

Heat Transfer Coefficients

The numerical model involves computation of heat transfer coefficients for the working fluid. Ardhapurkar et al. [10] applied different correlations to calculate the condensation heat transfer coefficients for multi-component mixtures in a MRJT cryocooler. In the present work, Shah correlation [11] has been taken for the estimation of the inner tube condensation heat transfer coefficient due to its simplicity. This condensation correlation is further modified using the Silver [12], Bell and Ghaly [13] correction to account for the mixture effect. Ardhapurkar et al. [14] also attempted to estimate the boiling heat transfer coefficients by employing various correlations. Based on the same, the Granryd correlation [15] is used to compute the annulus boiling heat transfer coefficient.

Using the above correlations, the inner (h_i) and outer (h_o) tube heat transfer coefficients are calculated. The overall heat transfer coefficient (U) is then found as shown below,

$$U = \left(\frac{1}{h_i} + \frac{r_1}{r_2} \frac{1}{h_o} \right)^{-1} \quad (1)$$

where r_1 and r_2 are the inside and outside radii of the inner tube respectively. The effect of the helical coil on the overall heat transfer coefficient (U_c) is considered by using the following equation [16],

$$U_c = U \left\{ 1.0 + 3.6 \left[1 - \left(\frac{D}{d} \right) \right] \left(\frac{D}{d} \right)^{0.8} \right\} \quad (2)$$

where D is the diameter of the heat exchanger tube and d is the helical coil diameter.

Methodology

In the current study, a one-dimensional steady state model is developed for a tube-in-tube counter-flow heat exchanger in a MRJT cryocooler. The LMTD method is utilized in the present model. Fig. 1 shows a schematic of a simple Joule Thomson cryocooler which is considered in the model. Firstly, once the inputs are given, the heat exchanger is divided into a number of segments (N). The temperature profiles for the hot and cold stream and the optimal heat exchanger length are then found using the flow chart given in Fig. 2.

The substantial variation in the thermo-physical properties with temperature along the heat exchanger length needs to be evaluated. The Peng-Robinson equation of state [17] has been found to be reliable for nitrogen-hydrocarbons mixtures [10]. As a result, the equation is used to calculate the thermodynamic properties of the refrigerant mixtures.

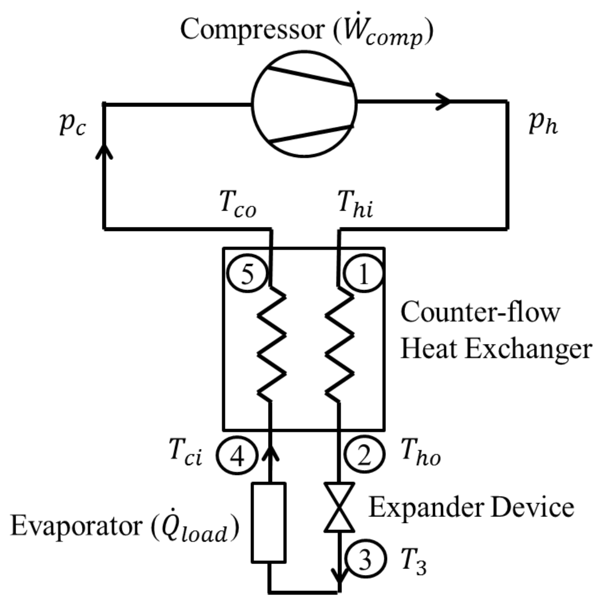

Figure 1. Schematic of a JT cryocooler

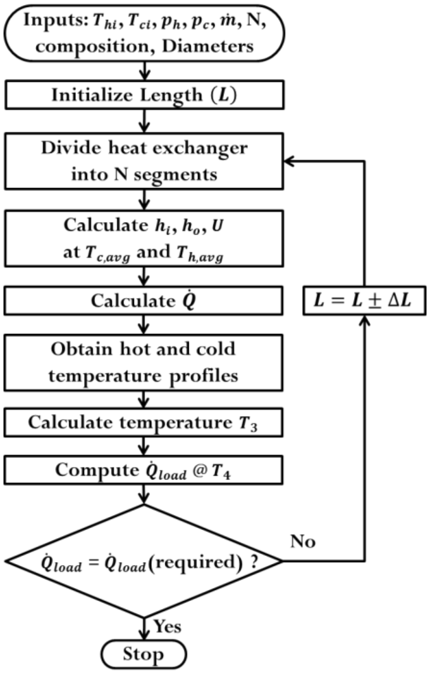

Figure 2. Flow chart for temperature profiles

Validation of the model

The numerical model explained in the previous section needed to be verified. For this purpose, experimental data presented by Ardhapurkar et al. [9] is utilized. Ardhapurkar used different mixtures in the MRJT cryocooler and measured the temperature distributions of hot and cold stream along the helical heat exchanger. The geometric parameters of the heat exchanger are given in Table 1 and the mixture specifications are given in Table 2. For the two mixtures, the operating conditions are given in Table 3. There is no heat load on the cryocooler for any of the mixtures. These are employed as input to the numerical model to get the temperature profiles and the optimum length.

Table 1 Specifications of the heat exchanger

Parameter	Value
Inner tube, ID (mm)	4.83
Inner tube, OD (mm)	6.35
Outer tube, ID (mm)	7.89
Outer tube, OD (mm)	9.52
Length of heat exchanger (m)	15
Coil diameter (mm)	200

Table 2 Refrigerant mixture specifications

Mixture	Circulation mixture composition $N_2/CH_4/C_2H_6/C_3H_8/iC_4H_{10}$ (mol %)
Mix#1	39.86/16.865/12.845/17.38/13.045
Mix#2	18.455/32.785/16.05/20.14/12.57

Table 3 Operating conditions

Mixture	$\dot{m}$ (g/s)	$P_{h,avg}$ (bar)	$P_{c,avg}$ (bar)	T_{hi} (K)	T_{ci} (K)
Mix#1	3.7	14.35	4.11	301.5	100.2
Mix#2	2.64	11.35	3.94	302.7	114.8

For Mix#1, the temperature distribution obtained is compared with the experimental readings as shown in Fig. 3. It can be see that the simulation results follow the trend of the experimental data. However, the simulation doesn't match exactly which may be due to the constant pressure assumption and the under-estimation of overall heat transfer coefficients. Similarly for Mix#2, the comparison of temperature profiles can be seen in Fig. 4. The numerical results are closer in the case of Mix#1 as compared to Mix#2. The simulation results help to determine the optimum length of the heat exchanger. Table 4 gives the simulation results. As can be seen, the optimal lengths are slightly greater than the actual lengths in the experiment. The reason for this could be the under-estimation of the heat transfer coefficients using the correlations.

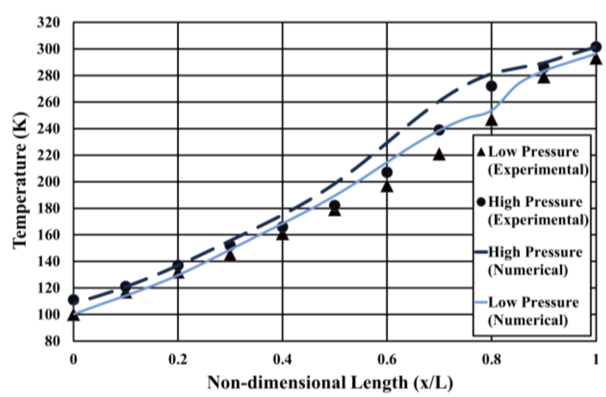

Figure 3. Temperature profiles for Mix#1

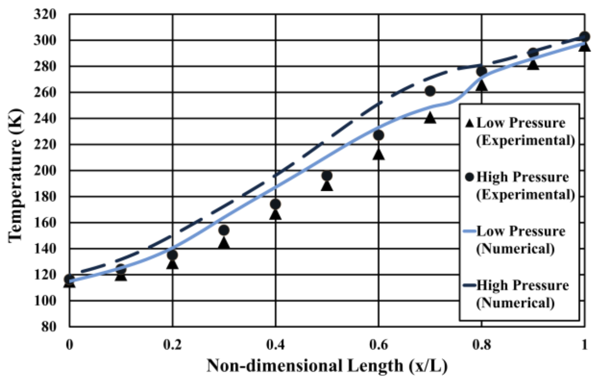

Figure 4. Temperature profiles for Mix#2

Table 4 Simulation results

Mixture	Average $U_{\exp}$ (W/m^{2}K)	Average U_{th} (W/m^{2}K)	$\dot{Q}_{\exp}$ (W)	$\dot{Q}_{th}$ (W)	L_{opt} (m)
Mix#1	1033.02	825.15	2180	2236.6	16.72
Mix#2	871.34	647.22	1765	1806.8	16.75

CRYOPRESERVATION CHAMBER

The validated numerical model is used to design the heat exchanger for the cryopreservation chamber. In the present case, the chamber has been designed to have a volume of about 75 L. The design cooling requirement is fixed as 40 W at 120 K using a 2 kW single stage compressor. The specifications of the MRJT cryocooler used for the cryopreservation chamber are given in Table 5. The optimum heat exchanger length is found to be 15.9 m. Fig. 5 shows the schematic of the proposed cryopreservation chamber.

Table 5 Operating conditions

Parameter	Value
Refrigerant Mixture Composition $N_2/CH_4/C_2H_6/C_3H_8/iC_4H_{10}$ (mol %)	12/22/22/22/22
Compressor Power (kW)	2
Design Cooling Load @120K (W)	40
Hot stream pressure (bar)	15
Cold stream pressure (bar)	3
Hot stream inlet temperature (K)	300
Cold stream inlet temperature (K)	120

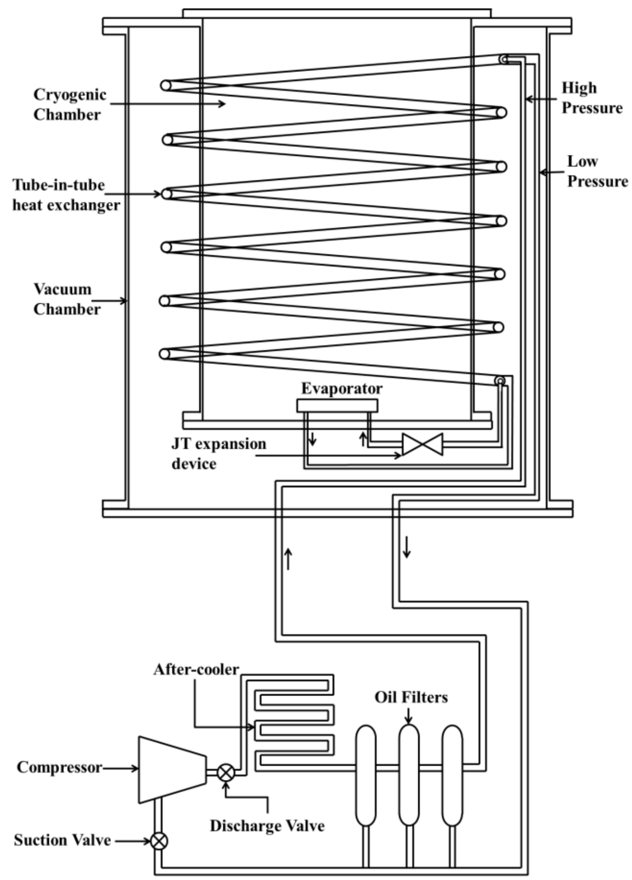

Figure 5. Proposed schematic of the cryopreservation chamber

CONCLUSION

A cryopreservation chamber has been designed which employs the MRJT technology. Since the performance of the heat exchanger critically affects the system, a numerical model is developed which determines the temperature profiles for both the hot and cold streams. The temperature distribution is then used to estimate the dimensions of the heat exchanger. The model is validated against experimental data from literature and subsequently, used to design the heat exchanger for the cryopreservation chamber. The specifications of the MRJT cryocooler utilized to cool the chamber have been selected as required and accordingly, the design of the cryopreservation chamber is finalized.

REFERENCES

1. Alexeev A., Thiel A., Ch. Haberstroh, Quack H., “Study of behavior in the heat exchanger of a mixed gas Joule-Thomson cooler”, *Adv. Cryogenic Eng.* Vol. 45, pp 307-315. (2000)
2. Keppler F., Nellis G., Klein S.A., “Optimization of the composition of a gas mixture in a Joule-Thomson cycle”, *HVAC&R Research*, Vol. 10(2), pp 213-230. (2004)
3. Burden D.W., “Issues in contamination and temperature variation in the cryopreservation of animal cells and tissue”, *International Biotechnology Laboratory*, Vol. 20(5), pp 20-29. (2002)
4. Berz D. and Colvin G., “Cryopreservation of Hematopoietic and Non-Hematopoietic stem cells—a review for the clinician”, *New Advances in Stem Cell Transplantation*. (2012)
5. Gong Maoqiong, Wu Jianfeng, Cheng Quiwei, Sun Zhaohu, Liu Jiayong and Hu Qinguo, “Development of a -186°C cryogenic preservation chamber based on a dual mixed-gases Joule-Thomson refrigeration cycle”, *Applied Thermal Engineering*, Vol. 36, pp 188-192. (2012)
6. Gong M.Q., Hu Q.G., Luo E.C. and Wu J.F., “Development of a cryogenic freezer based on the mixture refrigeration cycle”, *Proceedings of 19th International Cryogenic Engineering Conference (ICEC19)*, Grenoble, France, pp 571-574. (2002)
7. Cryogenic freezers, Panasonic Company.
8. Cryogenic storage chest freezers, Thermo scientific Company.
9. Ardhapurkar P.M, Sridharan A., Atrey M.D., “Experimental investigation on temperature profile and pressure drop in two-phase heat exchanger for mixed refrigerant Joule-Thomson cryocooler”, *Applied Thermal Engineering*, Vol. 66(1), pp 94-103. (2014)
10. Ardhapurkar P.M., Sridharan A., Atrey M.D., “Performance evaluation of heat exchanger for mixed refrigerant J-T cryocooler”, *Cryogenics*, Vol. 63, pp 49-56. (2014)
11. Shah M.M., “A general correlation for heat transfer during film condensation inside pipes”, *International Journal of Heat and Mass Transfer*, Vol. 22(4), pp 547-556. (1979)
12. Silver L., “Gas cooling with aqueous condensation”, *Trans. Inst. Chem. Eng*, Vol. 25, pp 30-42. (1947)
13. Bell K.J. and Ghaly M.A., “An approximate generalized design method for multicomponent/partial condenser”, *AIChE Symp. Ser*, Vol. 69, pp 72-79. (1973)
14. Ardhapurkar P.M., Sridharan A., Atrey M.D., “Flow boiling heat transfer coefficients at cryogenic temperatures for multi-component refrigerant mixtures of nitrogen-hydrocarbons”, *Cryogenics*, Vol. 59, pp 84-92. (2014)
15. Granryd E., “Heat transfer in flow evaporation of non-azeotropic refrigerant mixtures-a theoretical approach”, *Proc. 18th Int. Congress Refrigeration*, Canada, pp 1330-1334. (1991)
16. Zhou Y., Yu J., Chen X. “Thermodynamic optimization analysis of a tube-in-tube helically coiled heat exchanger for Joule-Thomson refrigerators”, *International Journal of Thermal Sciences*, Vol. 58, pp 151–156. (2012)
17. Peng, D. and Robinson, D.B., “A new two-constant equation of state”, *Ind. Eng. Chem. Fundam.* Vol. 15 (1), pp 59-64. (1976)

NOMENCLATURE

ID	Inside diameter (mm)
OD	Outside diameter (mm)
Mix#1	Mixture 1
Mix#2	Mixture 2
p	Pressure, (bar)
T	Temperature (K)
$\dot{m}$	Mass flow rate (g/s)
$\dot{Q}$	Heat transfer rate (W)
$\dot{Q}_{load}$	Cooling load (W)

Subscripts

c	cold fluid
h	hot fluid
ci	cold inlet
hi	hot inlet
co	cold outlet
ho	hot outlet
avg	average value
exp	experimental value
th	theoretical value
opt	optimum value