Experimental analysis to predict the performance of a plate fin heat exchanger at cryogenics temperature

Ajay K. Gupta, Manoj kumar*, Debashis Panda, Ranjit K. Sahoo

Cryogenics Engineering Laboratory, Department of Mechanical Engineering,
NIT Rourkela 769008, India

manoj526beg@hotmail.com

ABSTRACT. *The objective of this study is to provide experimental data that could be used to predict the effectiveness and performance of a plate fin heat exchange for low-temperature conditions. In this study, plate-fin heat exchangers are tested with a variation of the mass flow rate. Such heat exchangers have high fin density and offer narrow passages for the fluid flow, which often leads to a significant pressure drop. An experimental setup is made in the laboratory to test the plate fin heat exchanger at cryogenic temperature. In this setup, compressed nitrogen gas will be passed through the plate-fin heat exchanger as a hot stream. The hot stream gas will be passed through a liquid nitrogen coil heat exchanger to cool the high-pressure gas. The cold gas is then passed as a reverse stream of the plate fin heat exchanger. The experimental setup is mounted to the measurement instrument like RTDs, Pressure gauge, Differential pressure gauge, Orifice plate flow meter, etc. The effectiveness of heat exchange will be calculated from the measured temperatures directly from the experiment. Also, the temperature drop will be obtained from the analyses. The effectiveness and temperature drop data are also obtained through numerical analysis and validate it with experimental results.*

RÉSUMÉ. *L'objectif de cette étude est de fournir des données expérimentales qui pourraient être utilisées pour prédire l'efficacité et la performance d'un échange de chaleur à ailettes de plaque dans des conditions de basse température. Dans cette étude, les échangeurs de chaleur à ailettes de plaque sont testés avec une variation du débit massique. De tels échangeurs de chaleur ont une densité d'ailettes élevée et offrent des passages étroits pour le flux de fluide, ce qui entraîne souvent une chute de pression importante. Une configuration expérimentale est réalisée en laboratoire pour tester l'échangeur de chaleur à ailettes de plaque à température cryogénique. Dans cette configuration, l'azote gazeux comprimé passera à travers l'échangeur de chaleur à ailettes de plaque sous forme de flux chaud. Le flux de gaz chaud passera à travers un échangeur thermique à serpentin d'azote liquide pour refroidir le gaz à haute pression. Le gaz froid est ensuite transmis en tant que flux inverse de l'échangeur de chaleur à ailettes de plaque. Le dispositif expérimental est monté sur l'instrument de mesure, comme les sondes RTD, le manomètre, le manomètre différentiel, le débitmètre à plaque à orifice, etc. L'efficacité de l'échange thermique sera calculée à partir des températures mesurées en provenance de l'expérience directement. En outre, la chute de*

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température sera obtenue à partir des analyses. Les données d'efficacité et de chute de température sont également obtenues par analyse numérique et validées à l'aide de résultats expérimentaux.

KEYWORDS: *plate-fin heat exchanger, aspen, experimental study.*

MOTS-CLÉS: *échangeur de chaleur à ailettes de plaque, aspen, étude expérimentale.*

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1. Introduction

The heat exchangers are widely used in various field such as aerospace, automobile, electronics cooling devices, etc. Shah and Sekulic (2003) presented a classification of the heat exchangers taking in several aspects mainly divided into regenerative and recuperative. A contextual background including design and its application of regenerator that used mostly for small equipment like pulse tube cryocoolers in cryogenics are described by Ackermann (2013). In a regenerator, fluid streams are passing through the heat exchanger surfaces one after the other by absorbing and releasing energy separately whereas in a recuperator energy is exchanged at the same time through a parting sheet.

In cryogenics, a variety of heat exchanger is used as explained in (Barron and Nellis, 2016), since it requires highly efficient heat exchanger for liquefaction of gases. Many researchers (Barron, 1985; Atrey, 1998; Kanoglu *et al.*, 2008) investigated its sensitiveness for the production of liquefaction of gases; Barron reported that no liquefaction is obtained if the effectiveness of heat exchanger is lower than 85%. The study of the process of heat transfer in the heat exchanger and its design methods have been explained critically by various authors and scholars (Kern and Kraus, 1972; Kays and London, 1984; Ozisik, 1985; Frass, 1989 ; Shah, 1999 ; Vance *et al*., 1963 ; Kakac *et al.*, 2002 ; Mikheyey, 1968). Based on design criteria on spacing or say compactness, the compact heat exchanger is one of the best types of heat exchanger.

A compact heat exchanger confirms greater than 700 m^2/m^3 of heat transfer area density. Therefore, the size is an essential factor in a specific application where the size and weight is a significant constraint which is defined by Shah. He also including characteristics and its classification in their reports. Hesselgreaves *et al.* (2016) stated the different forms of compact heat exchanger employed for industrial uses. A general idea of fins in the heat exchanger for an automobile as well as in air conditioning system developed by Cowell and Achaichia (1997) and Webb (1998). Li *et al.* (2011) reports the different types of compact heat exchanger like plate heat exchanger, printed circuit Heat exchanger, plate fin heat exchanger, spiral heat exchanger, Marbond heat exchanger, ceramic heat exchanger, etc. However, for large equipment high compactness, multifluid flow plate fin heat exchanger provides the best result amongst other (Linde; Crawford and Eschenbrenner, 1972; Finn *et al.*,1999). As it is a multi-streams, many streams can be accommodated within a one compact heat exchanger unit. Consequently, the number of the item is to reduce or remove to reduce its weight and size.

The high-quality work on compact heat exchanger was reported by A.L.London (1984). He has also co-authored in a monograph with W.M.Kays and R.K.Shah and London (1978). Earlier in 1940 Kays (1948) carried out experimental works on heat exchangers and explained the test method for heat transfer and fluid flow characteristics. The literary work of Kays and London was adopted by various researchers. Even Kays and London also followed their developed data in their further studies on correlations and other related experiments.

Various authors have reflected on the design and development of PFHX by considering the material selection to shape, size, weight and surface design (Lenfestey, 1961; Lenfeste). Hesselgreaves proposed one of the important procedure for selection, design and operational process. In 1961, Lenfestey (1961) presented a review of the design method and the construction processes of the low-temperature heat exchanger. Later on, Lenfestey (1968) in 1968 added up further details in the following publication and proposed advanced heat exchanger.

The material employed for plate fin heat exchanger depends according to the requirement for temperature, pressure, and spacing. The temperature ranging up to 50oC; paper is used (mainly for ventilation purpose), for higher temperature up to 840 of metal is preferred, and for much higher temperature up to 1370 of ceramic materials are used. The metallic material required for plate-fin heat exchangers are aluminum, stainless steel, copper alloy, nickel alloy (Manglik *et al.*, 2011). Recently Seara and Uhia (2013) presented PFHXmade up of titanium brazed offset fins strip. Ceramates Inc, (Cermatec) design a ceramic heat exchanger. According to Taylor, (1987) aluminum is the desired material for cryogenic applications. Sarma *et al.* (2017) investigated the effect of fouling factor on the thermal performance of a heat exchanger tubes.

2. Experimental setup and procedure

The experimental setup comprises with counterflow offset plate fin heat exchanger as a test piece along with other components whose details are described below. The pressurized nitrogen gas from the liquid nitrogen storage tank through the vaporizer is made to pass through the plate fin heat exchanger on the high-pressure side and is chilled with the help of chiller and pass again to the low-pressure side. This session describes the major parts of the component, the arrangement of the experimental set-up and the calibration process of the apparatuses used.

In this experiment, the mass flow rate for both the side is set to be the same and constant for a single set of analysis. Proper measurements of outlet and inlet temperatures and pressure are measured when flow achieves steady state. The same process is repeated for different mass flow rate. The pressurized nitrogen as a working fluid from the vaporizer is collected in the reservoir tank and made to pass. The impurities of gas affect the experimental results and increase the fouling factor, which affects the performance of the heat exchanger. Therefore, Nitrogen gas supplied to the test system is of highly pure to avoid the fouling factor. Control valve manages to bring the flow of nitrogen gas at different flow rates. The gas enters to the high-pressure entry side of the heat exchanger and comes out from the high-pressure exit side and then it is allowed to pass through the chiller unit. The chiller unit is comprised of the cryogenic vessel (wide neck Dewar) in which a coil type heat exchanger is dipped in the liquid nitrogen bath in which the temperature of nitrogen gas decreases. Then the chilled gas is again sent back to the heat exchanger through the low-pressure entry side of the heat exchanger where it exchanges the heat from high temperature to the low temperature. After that, nitrogen gas comes out from the heat exchanger through the low-pressure exit side of the heat exchanger.

In the course of the flow process, valves and taps have to be evaluated in support of the performance perspective of the heat exchanger. For this purpose, instrumentation is added to the test rig for measuring the pressure, temperature and the mass flow rate. Pressure gauges are placed at the inlet on the hot side and provide at the outlet of the cold side to measure the pressures of the fluids. The U-tube manometers are coupled with a high-pressure side and low-pressure side, to estimate the drop in pressure on both sides of the heat exchanger. A provision is added to attach the RTD module along with the data adequate system for the measurement of temperature at the inlets and outlets of the hot and cold streams. Unconventional automation designs consist of six RTD response channels ADAM-4015 enclosed with ADAM-4520, which is connected to the computer. It is used for sensing different temperatures at different points of the test setup.

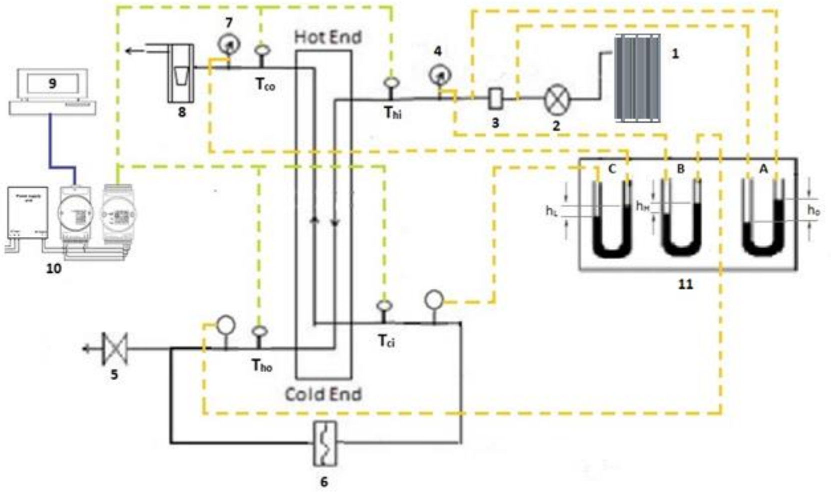

Figure 1. Process Flow &Instrumentation diagram of the experimental test rig

Details of instrumentation

1: Vaporizer	2: Control Valve
3: Orifice	4: Inlet Pressure Indicator
5: Bypass valve	6: Chiller Unit (Sub cooler)
7: Outlet Pressure Indicator	8: Rotameter
9: Monitor	10: ADAM View
11: Manometer’s	

$T_{hi}, T_{ho}, T_{ci}, T_{co}$: *PT100 Resistance Temperature Detectors (RTD’s).*

The required section is carefully insulated separately. The pipe connections are adequately wrapped with insulation tapes along with perlite powder casing, and the heat exchanger is shielded with perlite powder supported with of thermocol sheets to reduce the thermal conduction as well as convection interacting with the environments as shown in Figure 2.

In Figure 1, green dotted lines indicate the Resistance Temperature Detector (RTD’s) connection with the test rig to the data adequate system (ADAM VIEW) while yellow dotted lines are linked with the manometer. Instrumentation and fittings are listed below (Figure 1). The photograph of the actual model during the commissioning process is in Figure 2.

Figure 2. Commissioning of the experimental set-up

2.1. Simple representation of fluid flow facility of experimental setup

Above explained fluid flow, facility of the experimental setup is clarifying by the schematic Fluid Flow diagram as shown in Figure 4. The fluid (nitrogen gas) from the vaporizer flows into the heat exchanger then comes out and goes into the chiller. After that, the chilled gas again comes back into the heat exchanger where it exchanges heat and comes out to the atmosphere.

Figure 3. Final expérimental setup

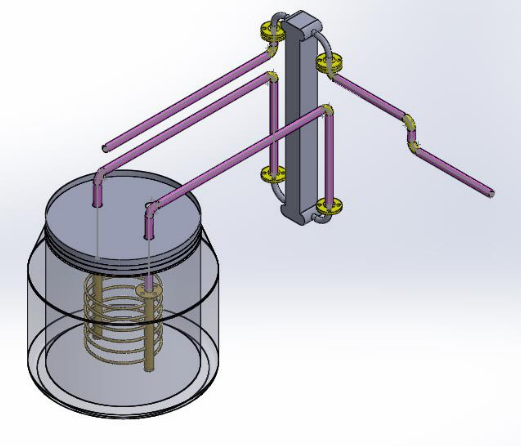

Figure 4. Schematic fluid flow diagram of experimental setup

2.2. Description of associated equipment and instruments

The experimental setup consists of the following component.

- Liquid storage tank unit
- Vaporizer
- Test Section (Plate Fin Heat Exchanger)
- Chiller unit
- Temperature measurement devices (RTD)
- Fluid metering device (Orifice or Rotameter)
- Pressure measurement devices (Manometers and Pressure Gages)

2.3. Storage tank

The storage tank of liquid nitrogen and other cryogens are often called as Dewar. The vessel name is in the name of its inventor called James Dewar. It is made up of two layers of the wall. Vessels have high levels of vacuum in between them to reduce the axial conduction and convection. The inner layer is of glass supported by an outer layer of metal for an extremely cold substance like liquid Helium, another layer of the liquid nitrogen shield is provided to reduce the evaporation rate.

2.4. Vaporizers

The vaporizer is a kind of heat exchanger, which is used to change the phase by transferring thermal energy from an external source of the fluid. Cryogenic liquid (N2) varies from a liquid state to the vapor state by exchanging heat with the ambient temperature.

There, are mainly two types of vaporizers

- Natural draft vaporizers

Natural draft vaporizers utilize free convection as the heat transfer mechanism. In the experiment, this type of vaporizer is used.

- Forced draft vaporizers

Forced draft vaporizers utilize forced convection as the heat transfer mechanism. Multiple fans mounted at the top of the vaporizer supplies high-velocity of air downward through the heat exchange array providing maximum heat transfer and high evaporation rates.

2.5. Plate fin heat exchanger

Table 1. Flow arrangement of the heat exchanger

	High-pressure side (Hot fluid side)	Low-pressure side (Cold fluid side)
Fin	Offset-strip fin (Osf)	Offset-strip fin (Osf)
No. of passage	5	4
No. of pass	Single	Single
Flow rate	Counter flow	Counter flow

Table 2. Core size of the heat exchanger

Core length	900 mm
Core width	73 mm
Core height	93 mm
Total length	1000 mm
Total width	85 mm
Total height	105 mm

Table 3. Fin Geometry of the heat exchanger

	FIN GEOMETRY	HIGH PRESSURE SIDE (Hot Fluid Side)	LOW PRESSURE SIDE (Cold Fluid Side)
1	Fin frequency, f	714 fins /meter	588 fins/ meter
2	Fin length, l	3 mm	5 mm
3	Fin thickness, t	0.2 mm	0.2 mm
4	Fin height, h	9.3 mm	9.3 mm
5	No. of layers	5	4

The high-pressure side has five layers, and the low-pressure side has four layers. Flow arrangement data is provided in Table 1. The core dimensions and fin geometry data has been tabulated in Table 2 and 3 respectively. The design data for this heat exchanger is given in Table 4.

Table 4. Flow parameters of the heat exchanger

	Hot side	Cold side
Fluid	Nitrogen	Nitrogen
Flow rate	5 g/s	4.8 g/s
Inlet temperature	310k	83.65 K
Outlet temperature	92.85 K	301.67 K
Allowable pressure drop	0.05 bar	0.05 bar
Pressure at inlet	7.35 bar	1.15 bar
Heat load	5.5 kW	5.5 kW

2.6. Chiller unit

The chiller unit consists of coil type heat exchanger dipped in a broad neck Dewar filled with liquid nitrogen. Liquid nitrogen extracts heat from the gaseous nitrogen. The temperature of nitrogen gas can be controlled by controlling the level of liquid nitrogen in the Dewar. The sub-cooler (chiller) is used for supplying cold gas to the plate fin heat exchanger. It is designed and developed in our cryogenics laboratory.

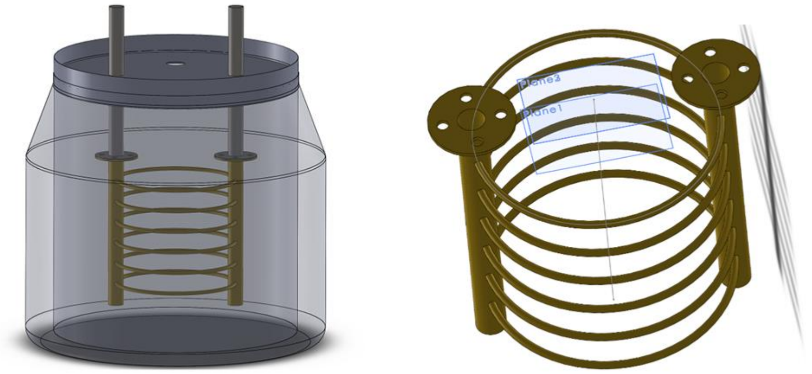

Figure 5. Design model of chiller heat exchanger

3. Results and discussions

The present work in this dissertation clarified the design criteria of the chiller to implement in the cold testing of plate fin heat exchanger. The LMTD method has been provided in the literature to estimate the length and number of tubes required for the Heat Exchanger. This new type of heat exchanger has been used as a chiller for obtaining cryogenic temperature. The concept is developed here for the implementation in experimental work.

It was concluded that the heat exchanger was explained by two main factors one is a low-pressure drop across inlet and outlet, and the other one is the high coefficient of performance. The equipment shown in Figure 5 is used for obtaining the outlet temperature up to 100K, and it will connect to the plate fin heat exchanger for cold testing. Nitrogen gas flow inside the tube and the tube dipped inside the liquid nitrogen. The outlet temperature of the nitrogen gas is controlled by refilling liquid nitrogen up to the certain interval of time using supply line. Figure 6 shows the inlet temperature and the liquid nitrogen temperature on which process is designed.

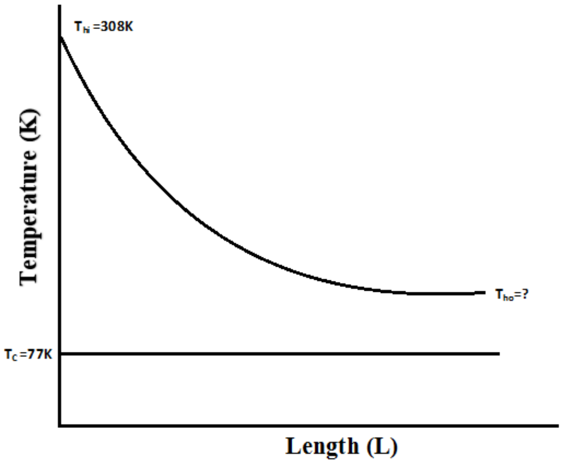

Figure 6. Temperature profile with respect to length

3.1. Numerical model

The heat transfer from liquid nitrogen in the wide neck cryogenic Dewar sustained at 196k ±0.5 K to hot gas flowing inside the coil was evaluated through CFD analysis and compared its result with the analytical solution. The CFD contour as shown in the result explains the outlet temperature, which verifies the analytical statement. An experiment was performed to analyze the predicted data developed by CFD. The recorded database shown in Table 5 represents the comparison and variation between the outlet temperatures of nitrogen gas flowing in a coil to that of the mass flow rate of nitrogen gas under the isothermal state.

3.2. Governing equations

Governing equations, which is used to solve the computational domain, are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla.\left(\rho U\right) = 0 \tag{1}$$

Momentum equations:

$$\frac{\partial\left(\rho U\right)}{\partial t} + \nabla.\left(\rho U \times U\right) = -\nabla p + \nabla.\tau + S_M \tag{2}$$

Where the stress tensor τ is related to the strain rate as:

$$\tau = \mu\left(\nabla U + \left(\nabla U\right)^T - \frac{2}{3}\delta\nabla.U\right) \tag{3}$$

Total Energy Equation:

$$\frac{\partial\left(\rho h_{tot}\right)}{\partial t} - \frac{\partial p}{\partial t} + \nabla.\left(\rho U h_{tot}\right) = \nabla.\left(\lambda \nabla T\right) + \nabla.\left(U.\tau\right) + U.S_M + S_E \tag{4}$$

Where h_{tot} is the total enthalpy, which is related to static enthalpy:

$$h_{tot} = h + \frac{1}{2}U^2 \tag{5}$$

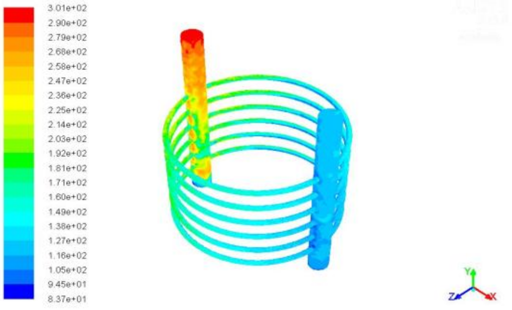

Figure 7. Temperature contour of heat exchanger of chiller

Table 5. Outlet Temperature as a function of mass flow rate

S.No.	Mass flow rate (Liter/min)	Outlet Temperature (K)		
		Analytical	Numerical	Experimental
1.	300	100.48	111.26	106.4
2.	350	106.14	114.46	111.4
3.	400	110.72	118.15	114.1
4.	450	116.01	122.35	118.3
5.	500	120.34	127.64	122.8

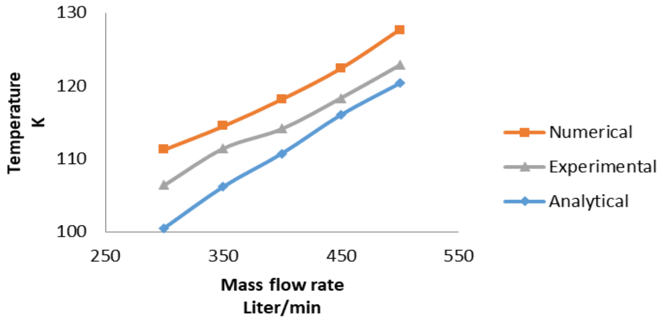

Figure 8. Temperature Vs Mass flow rate variation

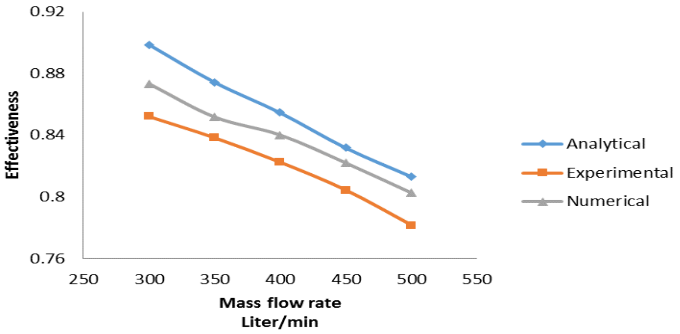

Figure 9. Effectiveness vs mass flow rate variation

Estimations were performed for various flow rates of nitrogen gas supplied by a gas vaporizer. The measurements are taken at steady state conditions. The cooling process is due to the absorption of heat by the liquid nitrogen, which boils off during the cooling process. Figure 8 demonstrates that the outlet temperature from the Chiller due to the change in the mass flow rate of the nitrogen gas. These show an increase in the outlet temperature as the mass flow rate increases. It also illustrates the minimum temperature 100.48K attended at 300 liters/min. Figure 9 represents the variation of the effectiveness of heat exchanger against the mass flow rate.

4. Conclusions

The experiment performed to evaluate the performance of a plate fin heat exchanger under cryogenic temperature. The performance of plate-fin heat exchangers in cryogenics environment was examined experimentally. An investigation is made to demonstrate the effect of mass flow rate on the effectiveness and the pressure drop. The obtained effectiveness and temperature drop find out from the numerical simulation are validated by experimental data and available correlations. Variation of effectiveness and temperature drop to mass flow rate gives the scheme to predict the performance of a specified heat exchanger. The outlet temperatures can be obtained from the predicted effectiveness. Comparison of the effectiveness of cold and hot tests are also added.

References

Ackermann R. A. (2013). *Cryogenic Regenerative Heat Exchangers.*

Atrey M. D. (1998). Thermodynamic analysis of Collins helium liquefaction cycle. *Cryogenics*, Vol. 38, No. 12, pp. 1199-1206. https://doi.org/10.1016/S0011-2275(98)00110-6

Barron R. F. (1985). *Cryogenic Systems*.

Barron R. F., Nellis G. F. (2016). *Cryogenic Heat Transfer*.

Ceramatec. *Compact Microchannel Heat Exchangers*.

Cowell T., Achaichia N. (1997). Compact heat exchangers in the automobile industry. *Compact Heat Exchangers for the Process Industries*, pp. 11-28.

Crawford D. B., Eschenbrenner G. P. (1972). Heat transfer equipment for LNG projects. *Chem. Eng. Prog.; (United States)*, Vol. 68, No. 9, pp. 62-70.

Fernández-Seara J., Diz R., Uhía F. J. (2013). Pressure drop and heat transfer characteristics of a titanium brazed plate-fin heat exchanger with offset strip fins. *Applied Thermal Engineering*, Vol. 51, No. 1, pp. 502-511. https://doi.org/10.1016/j.applthermaleng.2012.08.066

Finn A. J., Johnson G. L., Tomlinson T. (1999). Developments in natural gas liquefaction. *Hydrocarbon Processing*, Vol. 78, No. 4, pp. 47-56.

Frass A. P. (1989). *Heat Exchanger Design.*

Hesselgreaves J. E., Law R., Reay D. (2016). *Compact Heat Exchangers: Selection, Design and Operation*.

Kakac S., Liu H., Pramuanjaroenkij A. (2002). *Heat Exchangers: Selection, Rating, and Thermal Design*.

Kanoglu M., Dincer I., Rosen M. A. (2008). Performance analysis of gas liquefaction cycles. *International Journal of Energy Research*, Vol. 32, No. 1, pp. 35-43. https://doi.org/10.1002/er.1333

Kays W. M. (1948). Description of test equipment and method of analysis for basic heat transfer and flow friction tests of high rating heat exchanger surfaces. *Technical Report*, No. 2.

Kays W. M., London A. L. (1984). *Compact Heat Exchangers.*

Kern D. Q., Kraus A. D. (1972). *Extended Surface Heat Transfer.*

Lenfestey A. (1961). Low temperature heat exchangers. *Progress in Cryogenics*, Vol. 3, pp. 25-47.

Lenfestey A. G. *Compact Heat Exchangers for Gas Separation Plant Proc.,* pp. 47-49.

Li Q., Flamant G., Yuan X., Neveu P., Luo L. (2011). Compact heat exchangers: A review and future applications for a new generation of high temperature solar receivers. *Renewable and Sustainable Energy Reviews*, Vol. 15, No. 9, pp. 4855-4875. https://doi.org/10.1016/j.rser.2011.07.066

Linde A. G. Aluminium plate-fin heat exchangers. *Catalogue. Cited on pages xiii, xix*.

London A. L. (1984). Compact heat exchangers. *Mechanical engineering*, Vol. 86, pp. 31-34.

Manglik R. M., Huzayyin O. A., Jog M. A. (2011). Fin effects in flow channels of plate-fin compact heat exchanger cores. *Journal of Thermal Science and Engineering Applications*, Vol. 3, No. 4, pp. 041004. https://doi.org/10.1115/1.4004844

Mikheyev M. (1968). *Fundamentals of Heat Transfer.*

Ozisik M. N. (1985). *Heat transfer: A Basic Approach.*

Sarma P. K., Konijeti R., Subramanyam T., Prasad L. S. V., Korada V. S., Srinivas V., Vedula D. R., Prasad V. S. R. K. (2017). Fouling and its effect on the thermal performance of heat exchanger tubes. *International Journal of Heat and Technology*, Vol. 35, No. 3, pp. 509-519. https://doi.org/10.1016/10.18280/ijht.350307

Shah R. K. (1999). *Compact Heat Exchangers and Enhancement Technology for the Process Industries*.

Shah R. K., London A. L. (1978). Laminar flow forced convection in ducts: A source book for compact heat exchanger analytical data. *Heat Transfer*.

Shah R. K., Sekulic D. P. (2003). *Fundamentals of Heat Exchanger Design*.

Taylor M. A. (1987). Plate-fin heat exchangers: Guide to their specification and use. *Heat Transfer and Fluid Flow Services*.

Vance R. W., Adelberg M., Buchhold T. A. (1963). *Cryogenic Technology.*

Webb R. L. (1998). Advances in air-cooled heat exchanger technology. *ASME*, Vol. 365, pp. 49-58.

Nomenclature

RTD	Resistance Temperature Detector

Subscripts

h_i	Hot inlet
h_o	Hot outlet
c_i	Cold inlet
c_o	Cold outlet
s_f	Strip fin