A Review on Highly Compact Perforated Plate Heat Exchanger for Cryogenic Applications

Patel Vinodkumar Babulal, Nisha V. Bora

Abstract— This paper describes a variety of fundamental research of cryogenic perforated plate heat exchanger which works at temperature 123K (-150°C) or below it, also it is most critical component used for separation, purification, liquefaction, refrigeration systems, working with different cryogenic gases like helium, hydrogen, neon, nitrogen, oxygen, air etc. Its primary function is “to converse cold” i.e. allow the removal of energy from the compressed incoming gas by transferring energy to the low-pressure cold stream. So, it is always desirable to prevent “heat inleaks” to the system, as it is more difficult to remove energy from the low-temperature regions. Also apart from having a high effectiveness, cryogenic heat exchangers also need to be very compact, i.e. they must accommodate a large amount of surface area in a small volume. This helps in controlling heat exchange with the surroundings by reducing exposed surface area. Perforated plate matrix heat exchanger (MHE) covers advantages of high effectiveness and high degree of compactness together in one unit used for cryogenic applications. This paper deals with the brief review of research articles in chronological development of perforated plate matrix heat exchanger.

Index Terms— Cryogenic, Highly compact, Highly effective, Hydrogen, Matrix heat exchanger, Perforated plate, Porosity

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1 INTRODUCTION

Heat exchangers are most crucial component in any process industries, for improving efficiency and decreasing cost of whole plant. A “heat exchanger” is defined as equipment which transfers the energy from a hot fluid to a cold fluid, with maximum rate and minimum investment and running costs. In some conventional systems, such as regenerative gas turbine power plants, the system will operate even if the heat exchanger is not highly effective, say less than 50%. In contract, a cryogenic liquefier will not produce liquid if the heat exchanger effectiveness is less than approximately 85%. [1, 2]

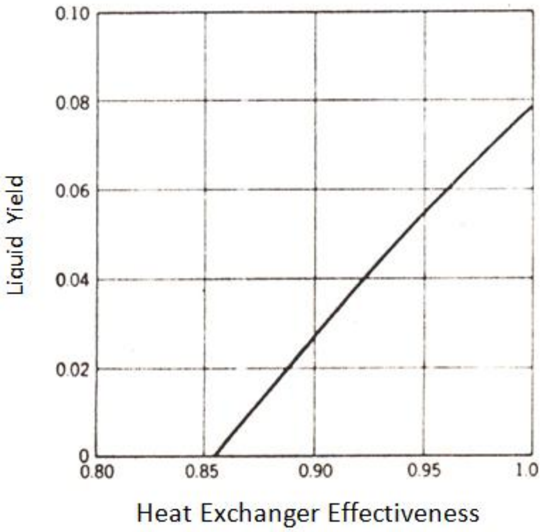

Fig.1 Effect of heat exchanger effectiveness on liquid yield

Heat exchangers are the main components in cryogenic processes. In air separation units and liquefaction of gas plants, they represent 20% to 30% of the investment costs. In addition, their performance affects the sizing and design of other major equipments, namely compressors and their power drivers. Thermodynamic considerations make cryogenic processes very sensitive to the heat exchanger performance. For example, a reduction of 22% in the production of liquid if the heat exchanger effectiveness departs from the ideal value of 100% to a more practical one of 96.5%. In the case of liquefaction of helium, it was calculated that if heat exchanger effectiveness is reduced from 97% to 95%, 12% less liquid is obtained. For nitrogen liquefaction by simple Linde-Hampson system, the effect of heat exchanger effectiveness on liquid yield is shown in Fig.1. It is clear from the figure that liquid yield is zero for effectiveness 0.869. An important consequence of heat exchanger under-performance is the need for modifications in the process to achieve the desired liquid production rate. The refrigeration capacity has to be increased, with the corresponding increase in power input, which is a major concern in cryogenics.

In short, if the heat exchanger has low performance, the production is reduced and large amounts of additional power input are required. This sets the need for high-effectiveness heat exchangers, in the order of effectiveness > 90%. [2, 3]

2 NON-NEGLIGIBLE EFFECTS FOR CRYOGENIC HEAT EXCHANGER

Traditional heat exchanger neglects some effects, since they are not relevant for the typical required engineering accuracy. However, the high-effectiveness requirements for cryogenic HEs make necessary to take these effects into account. [15] They include: changes in fluid properties, heat exchange with the surrounding (heat leakage), longitudinal thermal conduction in the wall, and flow maldistribution. The relative importance of these effects is summarized in Fig. 2.

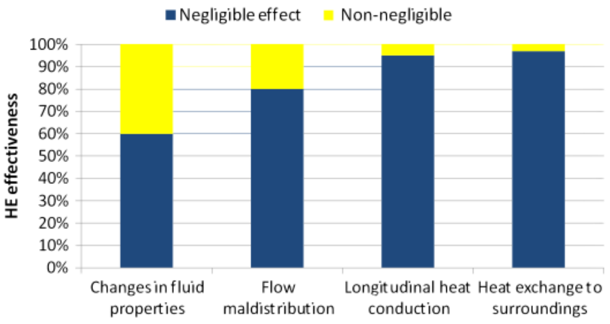

Fig. 2 Non-negligible effects for cryogenic heat exchanger

For low-efficiency applications, all of them can be neglected. For higher effectiveness requirements, they all need to be considered, in increasing order of accuracy: changes in fluid properties, flow maldistribution, longitudinal conduction and heat leakage. These considerations depend on the particular operating conditions and cover relatively wide and approximate ranges. The following subsections present some details of these effects.

2.1 Changes in fluid Properties

Main distinctive feature of cryogenic heat transfer is that all constants become variables. For single-phase flow, the main effect is given by changes in the specific heat capacity. In the case of two-phase flow, this is accompanied by large variations in the heat transfer coefficient, as well as density and viscosity. The analysis of high-temperature HEs is not applicable for cryogenic applications.

2.2 Flow Maldistribution

Non-uniformity in fluid flow is one of the primary reasons resulting in a poor heat exchanger performance. This may be attributed to improper design of inlet/outlet port and header configuration, distributor construction and plate corrugations. In many scenarios, the flow distribution can deviate from design conditions, usually homogeneous. The causes of maldistribution includes mechanical issues such as fouling, fabrication tolerances, bypass and poor header performance, two-phase instabilities, and heat-transfer induced as a consequence of changes in viscosity or density. Flow maldistribution results in a deterioration of performance of single-phase HE, although this effect is only relevant for high efficiency equipment such as those used in cryogenics. The effect on two-phase flow systems is more complicated, and both a reduction and an increase in performance have been observed.

2.3 Longitudinal Thermal Conduction

This effect reduces the local temperature difference between the working fluids and the separating wall, deteriorating the heat transfer. In the extreme case of infinite thermal conductivity, the performance of a balanced counterflow HE is reduced roughly by half. This effect is more significant in small systems with short conduction lengths, such as perforated-plate, than in the large coil-wound (CWHE) and plate-fin (PFHE) heat exchangers.

2.4 Heat-in-Leakage

Since cryogenic processes operate at much lower temperaturethan ambient, cryogenic equipment exchanges heat with the surroundings. The development of multilayer insulations has reduced the heat-leakage to a practical minimum. However, when high-effectiveness equipment is required, this effect has to be considered. [3]

3 PERFORATED PLATE MATRIX HEAT EXCHANGER

Perforated plate exchangers consist of stacks of parallel perforated metal plates of high thermal conductivity with gaps between the plates formed by spacers of plastic or other low-conductivity material. The spacers are firmly bonded to the metal plates. They serve not only to minimize conduction from one plate to another but also to separate the high-pressure and low-pressure gas streams and confine their flow to particular clusters of perforations in the plates. The compact model of perforated plate heat exchanger is shown in Fig. 3.

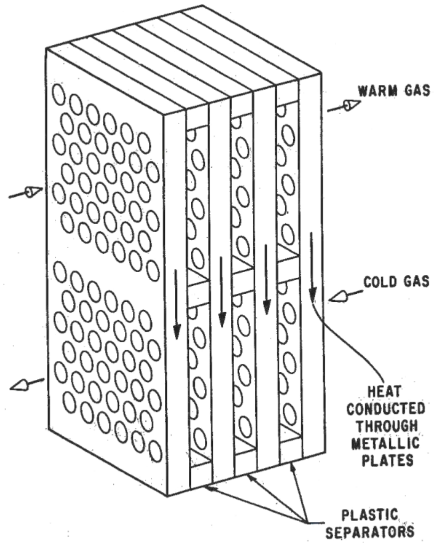

Fig. 3 Compact perforated plate heat exchanger

The working principle of the perforated plate exchanger is shown in Fig. 4. It is also called rectangular perforated plate heat exchanger. It consists of a large number of parallel perforated plates with gaps between the plates. The plates are made of high-conductivity metal (copper or aluminium) but the spacers between the perforated plates are constructed of low-conductivity material (plastic or stainless steel). The spacers

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are bonded to the metal plates and serve to minimize thermal conduction between the plates and confine the high-pressure and low-pressure flows to selected clusters of perforations on the plates.

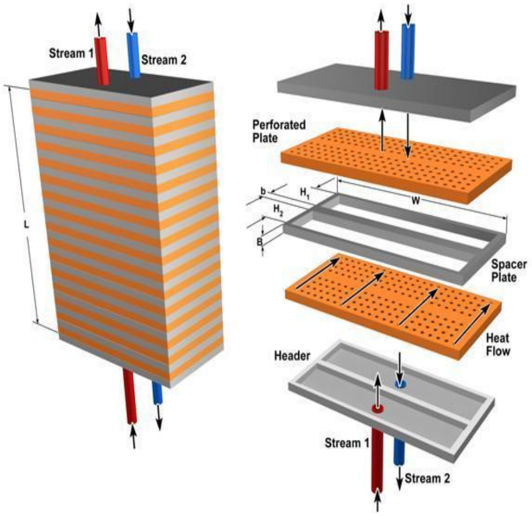

Fig. 4 Working principal perforated plate heat exchanger

The fluids flow in counter-flow direction and heat transfer occurs laterally from one stream to another through the plates. Very small perforations can be made in the plates so that a large heat transfer surface area per unit volume can be developed. The gaps between plates allow a very uniform flow across the section. Moreover, since the length/diameter ratio is very small for each hole in the plate. So, the thermal and hydrodynamic boundary layers are broken up before they have a chance to become fully developed. This results in very high heat transfer coefficient and consequently high friction factors. [4,5]

4 CHRONOLOGICAL DEVELOPMENT OF PERFORATED PLATE MATRIX HEAT EXCHANGER

The necessity of high effectiveness in a small volume has led to the development of perforated plate matrix heat exchangers (MHE) for cryogenic applications. The survey for perforated plate heat exchanger with Investigator and Year is summarized as follows.

McMahon et al. (1949) [5] was the first introducer of perforated plate matrix HE. He has used aluminium as a perforated plate material and thin neoprene gaskets (die cut) as a spacer material (served to separate the fluid streams, provide gas tight seal at liquid air temperature).

Fabrication and bonding technique: Cast aluminium header at each end, held together by steel tie rods. Construction is simple & easy to repair. Application: For production of liquid oxygen.

Garwin R.L. (1966) [5] had investigated and first time patented circular geometry. Spacer material: Neoprene & nylon (not very successful, as developed sealing problem at low temperature, particularly after thermal cycling). Fabrication and bonding technique: Cylindrical geometry (For elemination of leakage of gas to surround-ings), Use of springs at both ends (For compensate dif-ferential concentration between heat exchanger core & support structure on cooling).

London A.L (1966) [5] had given the heat transfer correlations for developing flow in matrix heat exchanger. He suggested that length to diameter ratio of perforated plate between 0.3 and 4.0 give high heat transfer coefficient. Flow through the tubular portion (length/diameter ratio) can be considered as developing flow associated with high heat transfer coefficient.

Fleming R.B. (1967) [5] had used perforated plate material: Copper (thermal conductivity, k=400 W/mK), Spacer material: Stainless steel (k=12 W/mK).

Fabrication and bonding technique: Bonded together by soldering, brazing or diffusion (solid state) welding. His work was first time patented as porous metal heat exchanger of US Patent 3 433 299 (1969).

Advantages: Thermal stresses developed during bonding and operation is small because of close coefficients of expansion of copper and stainless steel. The probability of forming hermetic seals between two metals is much higher than between a metal and a plastic. A metal shows less deterioration in ductility on ageing than plastics.

Vonk G. (1968) [6] had introduced bonding technology for both 1. Wire screen & resin and 2. Perforated plate & plastic spacer heat exchangers.

General Electric Corporation, USA (1969) [5] had lead to development of matrix heat exchanger made of perforated plate material: aluminium and spacer material: plastic (k< 1W/mK) for helium liquefier development program. The exact specifications of the plastics and the adhesives used have not been published in open literature.

Fleming R.B. (1969) [7] had done modelling work of matrix heat exchanger. He was considering perforated plate as fin or the secondary surface with certain fin efficiency. Fleming considered the effect of axial conduction and expressed his results in terms of an apparent NTU (Number of transfer units).

Fleming got good agreement between computed and experimental performance for the range of exchangers that he constructed. The small flow passage (typically 0.3-1.0 mm diameter) ensures high heat transfer coefficient & high surface area density.

Ostbo, K.R.A (1969) [5] had patented a matrix ex-changer with demountable seals for use in liquid to liquid and liquid to gas heat exchangers at near ambient temperatures. Although demountable assembly had advantages such as flexibility, reusability and low cost. Elastomeric gaskets pose serious problems, as they tend to harden at low temperatures and develop cracks on temperature cycling.

Kim J.C., Qvale E.B. (1971) [8] had given alternative approach to matrix heat exchanger design. They have used a pin fin model to represent wire screen exchangers, but their results are also applicable to perforated plate units.

Lins R.C, Elkan M.A (1975) [5] had used perforated plate material as woven wire screens in perforated plate type heat exchanger.

Orlov V.K. (1978) [5] had shown that the heat transfer coefficient and friction factor do not vary significantly with spacer thickness. In 1980 they had shown that the heat transfer coefficient and friction factor do not vary significantly with spacer thickness.

Sarangi S., Barclay J.A (1984) [5] had shown that the maximum attainable NTU per plate is 1.0. Experimental results, recently reported by Hubbell and Cain (1986), support this conclusion.

Hitachi Corporation, Japan (1986) [5] had developed perforated plate matrix heat exchanger for use in a small Claude cycle cryorefrigerator based on microturbine expander.

Merida W.R, Barclay J.A (1998) [9] had reported that in the second stage regenerator of Gifford-McMahon cryocooler, use of perforated Nd(neodymium) plates instead of packed bed of particles, large cooling capacity achieved by reducing effective porosity thereby increasing the thermal mass per unit volume.

Frangois Viargues, Gerard Claudet, Peter Seyfert (1994) [10] had presented the paper on "Construction and Preliminary Testing of Perforated-Plate Heat Exchangers" will concentrate on combine pressure losses in the cold gas stream is as low as a few milli-bars with thermal efficiencies close to 95 %. The only way to achieve this goal is to provide large flow cross-sections and short flow paths. In conventional aluminium plate-fin exchangers, design concept produces large heat losses by axial conduction through the body of the exchanger made of high conductivity material. As a result, the thermal efficiency drops dramatically. Coiled tube exchangers have the same disadvantage.

Perforated-plate heat exchangers seem to offer better overall performance than plate-fin heat exchanger, by virtue of their particular configuration they allow high thermal conductance in transverse direction while low thermal conductance in axial direction. They had select copper as a perforated plates, stainless steel as a spacers, hole diameter less than 1 mm, plate & spacer thickness=0.5 mm for heat exchanger.

Guo Tingwei, Zhu Tingying, Hu Jichuan and Gong Linghui (1996) [11] had reported that Claude-cycle cryogenic refrigerators require a highly effective compact counter-flow heat exchanger. Perforated-plate heat exchangers have been gradually developed so as to satisfy these needs. In the design of a perforated-plate heat exchanger, the plate thickness, hole diameter, hole centre pitch (porosity) and plate pitch are very important geometric parameters.

O.P. Anashkin, V.E. Keilin, V.M. Patrikeev (1976) [12] had noted that, the more efficient and portable heat exchanger is one of the more important project in cryogenic engineering for improving heat transfer. Vonk G. and Fleming R.B. described heat exchangers with large heat transfer surface area per unit volume. The heat transfer surface area per unit volume of perforated-plate heat exchangers can be as high as 6000 m^2/m^3, which is about ten times higher than the corresponding value for conventional heat exchangers. They had used copper plate thickness=0.5 mm, spacer plate thickness=0.3 mm, hole diameter=1.5 mm, hole pitch=2.0 mm for their research work.

G. Venkatarathnam, Sunil Sarangi (1990) [5] had presented paper on "Matrix heat exchangers and their application in cryogenic systems". This paper traces the different methods of fabrication, heat transfer and fluid flow characteristics and some basis of design of the perforated plate MHE. They reported that, "This work was supported by the Department of Non-Conventional Energy Sources, Ministry of Energy, Government of India under the project, Liquid hydrogen: production, storage and transfer."

Michael J. Nilles, Myron E. Calkins, Michael L. Dingus, John B. Hendricks (1995) [13] had reported that the principal reason for developing perforated plate heat exchangers is that they are extremely compact. Perforated plate heat exchangers are ideal for high flow rate applications, since the resulting exchanger is almost certain to be smaller than a comparable exchanger of different design. Because longitudinal thermal conductivity can be separately controlled by the choice of spacer material, perforated plate heat exchangers may also offer significant advantages in low flow rate, low pressure drop applications.

K. Krishnakumar, G. Venkatarathnam (2003) [14] had noted that conventional cryogenic heat exchangers such as coiled tube heat exchangers of Hampson and Collins types and brazed aluminum plate fin exchangers are not suitable for small systems used in satellites. Because of the large longitudinal (axial) heat conduction through the walls and the heat leak from ambient, which limit the maximum achievable effectiveness to about 92%. In a perforated plate heat exchanger the flow cross-section changes continuously between that of the perforations and the spacer, the perforations being smaller than the spacer. Consequently, the fluid undergoes alternate expansion and contraction as it flows through the exchanger. Because of the interruption of the boundary layer at every plate, the flow through the tubular portion can be considered as developing flow, associated with high heat transfer coefficient. They had suggested length (plate thickness) to diameter ratio=0.3-4.0, flow passage=0.3-1.0 mm in diameter.

5 COMPACT SIZING OF PERFORATED PLATE MATRIX HEAT EXCHANGER

G. Venkatarathnam had presented a paper on, "A Straightforward Method for the Sizing of Perforated Plate Matrix Heat Exchangers". In this paper closed-form expressions are presented for the effectiveness of matrix heat exchangers in terms of different resistances. These expressions can be used to determine the effectiveness of matrix heat exchangers of any shape (circular, rectangular etc.). Based on these expressions, a procedure is developed for the sizing of balanced flow perforated plate matrix heat exchangers.

The optimum design procedure has been used to evaluate the size of perforated plate matrix heat exchanger operating at an effectiveness of 95%, helium as the working fluid, mass flow rate is 0.2 g/s in either channel and allowable pressure drop of 1500 Pa. Hot stream inlet temperature, $T_{h,in}$ = 300 K & cold stream inlet temperature, $T_{c,in}$ = 80 K. The geometry of the exchanger estimated, along with the different dimensionless parameters is presented in Table 1.

TABLE 1
Estimated Geometry of the Heat Exchanger

Variable	Cold Fluid Channel	Hot Fluid Channel
Hole diameter (d_h), (Input)	0.5 mm	0.2 mm
No.of plates (N_p)	94	
Width (W_p)	56.35 mm	
Plate height (H)	5.19 mm	0.99 mm
Plate porosity (p), (Input)	22%	22%
Pressure drop (ΔP)	1500 Pa	7250 Pa
Fin effectiveness (η_f)	77%	95%

6 CONCLUSION

- Conventional aluminium plate-fin & coiled tube heat exchangers produce large heat losses by axial conduction through body of exchanger made of high conductivity material. As a result, the thermal efficiency drops dramatically. Also they not suitable for small systems, as maximum achievable effectiveness to about 92%.
- By virtue of particular configuration perforated-plate heat exchangers offers better overall performance than plate-fin heat exchangers on following aspects:
  - It allows high thermal conductance in transverse direction and low thermal conductance in axial direction.
  - Heat transfer surface area per unit volume is 6000 m^2/m^3, is ten times higher than conventional heat exchangers.
  - High effectiveness and high degree of compactness together in one unit.
  - Fuid undergoes alternate expansion and contraction as it flows through the exchanger, results in high heat transfer coefficient.
  - From Table 1, it is evident that perforated-plate heat exchanger is extremely compact.
- Perforated plate matrix heat exchangers are finding increasing cryogenic application withconsiderable savings in volume and cost.

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