Porous-medium modelling for CFD simulation of perforated plate heat exchangers for cryogenic applications

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Abstract

A novel porous medium approach using Ansys Fluent™ is presented for modeling perforated plate heat exchangers (PPHEs). New correlations for the plate-permeability and Forchheimer coefficient are presented for a Reynolds number range of 30<Re<500 and a porosity range of 0.2 to 0.27. The thermal performance of PPHEs is done using the local thermal equilibrium approach. The model agrees well with the published experimental data of PPHEs for both inline and shifted hole arrangements.

Introduction

Construction-wise, a PPHE is a stack of alternately arranged high conductivity perforated plates and insulating spacers, as shown in Fig.1. Being compact (area density as high as 6000 m²/m³), it is used in many applications, including 2K superfluid helium cryogenic system. The major issue in the CFD simulation of a PPHE is the inclusion of tiny holes (≈0.6 mm diameter) in the computational domain that would result in a huge cell count. This is mitigated by adopting each perforated plate as a porous medium. The Darcy-Forchheimer equation[1] has been utilized to determine the pressure drop through the heat exchanger. In this method, a pressure gradient as a source term is used in the momentum equation in which we need permeability (K) and Forchheimer coefficient (β). These have been obtained from the available pressure drop data on PPHEs. Thermal modeling is done using local thermal equilibrium approach. The predictions compare well with the reported experimental data.

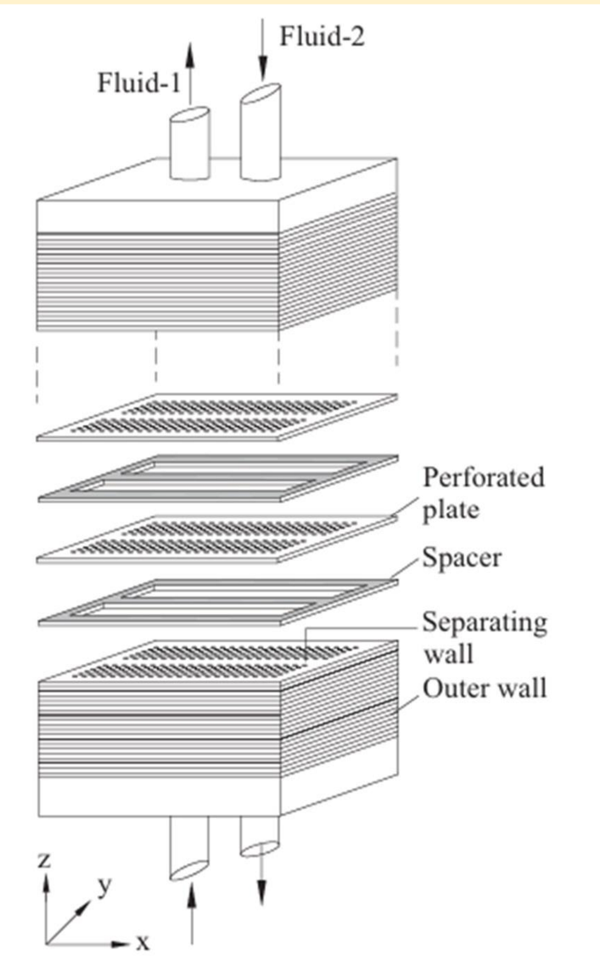

Fig. 1. Construction of a PPHE

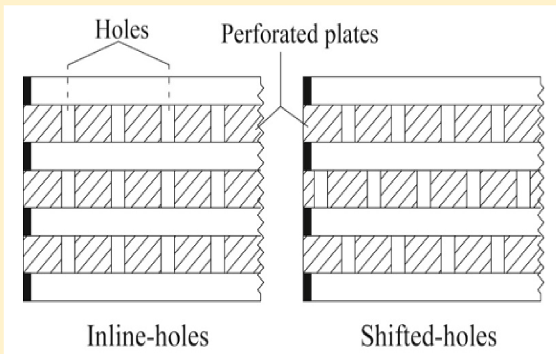

Fig. 2. Inline and shifted hole arrangements

Nomenclature

d= Pore diameter
f_{Loss}= Spacer Pressure loss factor
K = Plate permeability
N_P = Number of Plate-spacer pairs
U_S= Superficial velocity
β = Forchheimer coefficient
δ_P = Plate thickness
δ_S = Spacer thickness
ϵ = Plate porosity
ρ = Fluid density
φ_v = Viscous dissipation
μ = Fluid viscosity

Pressure drop Modelling

Assumption: 1. In a porous medium for very low Re (<=10), only viscous losses contribute to pressure drop, and inertial losses are neglected.

2. For inline holes the pressure drop in spacer regions is neglected. Since pores of consecutive plates are in alignment, and spacer thickness is very small, so the fluid can pass from plate to plate easily.

Equations used:

Darcy Equation used for Re=10: $\frac{\Delta P}{\delta_p} = \frac{U_s}{K}$ (1)

Darcy-Forchheimer equation for Re>10: $\frac{\Delta P}{\delta_p} = \frac{\mu U_s}{K} + \beta\rho U_s^2$ (2) for inline holes, and for shifted holes $\frac{\Delta P}{\delta_p} = \frac{U_s}{K} + \beta'\rho U_s^2$ (3)

$$\Delta P_{shifted\text{-}holes} = \Delta P_{inline\text{-}holes} + \Delta P_{spacers} = \left(\frac{\mu U_s}{K} + \beta\rho U_s^2\right) N_p \delta_p + \left(\frac{f_{loss}}{2}\rho U_s^2 N_p\right) \quad (4)$$

Rearranging and comparing with eq.(3), we get $\beta' = \beta + \frac{f_{loss}}{2\delta_p}$ (5)

Using the reported data through numerical predictions on pressure losses in various combinations of geometrical and flow conditions [2], the correlations for K, β and β′ are calculated.

Determination of K, β and β′ **

1. K of plate: For a given plate geometry at Re=10, K is calculated from eq(1) where ΔP is obtained from the literature data [2]. A large number of geometry is considered and empirical correlation for permeability is obtained as,

$$K = 0.031445\,(\epsilon)^{1.0416}(\delta_S)^{-0.178524}(\delta_P)^{0.3984}(d)^{1.8116} \quad (6)$$

2. β for Inline holes: For Re>10, β is calculated for various plate geometry and different Reynolds number from eq.(2) and correlations are obtained as,

$$\beta = (\delta_P)^{-1}(\delta_S)^{0.71073}(d)^{-0.3776}(\epsilon)^{-2}(Re_P)^{-0.1071} \quad \text{[for 30<Re<100]} \quad (7)$$

$$\beta = (\delta_P)^{-1}(\delta_S)^{0.82046}(d)^{-0.89184}(\epsilon)^{-2}(Re_P)^{-0.6913} \quad \text{[for 100<Re<500]} \quad (8)$$

3. β′ for Shifted holes:

Considering, $\Delta P_{spacers} = \Delta P_{shifted\text{-}holes} - \Delta P_{Inline\text{-}holes}$ (9)

RHS of eq.(9) for a given geometry and flow is computed from ref. [2] and β′ is calculated from eqs.(4) and (5). The following correlations are obtained.

$$\beta' = 0.3125\,(\delta_P)^{-1}(\delta_S)^{-1.04719}(d)^{0.9713}(\epsilon)^{-2.6003}(Re_P)^{-0.40677} \quad \text{[For 30<Re<100]} \quad (10)$$

$$\beta' = 0.3226(\delta_P)^{-1}(\delta_S)^{-0.35989}(d)^{0.4424}(\epsilon)^{-2.4374}(Re_P)^{-0.02322} \quad \text{[For 100<Re<500]} \quad (11)$$

**The above correlations are valid for $0.5 < \frac{\delta_S}{\delta_P} < 2$ and $0.5 < \frac{\delta_P}{d} < 0.9$ and $0.2 < \epsilon < 0.27$.

Pressure drop per unit length from the Darcy-Forchheimer equation works as a source term to the Navier-Stokes momentum equation, representing momentum loss for flow through perforated plates.

$$\frac{\partial(\epsilon\rho\vec{v})}{\partial t} + \nabla.(\epsilon\rho\vec{v}\vec{v}) = -\epsilon\nabla P + \epsilon\overrightarrow{B_f} + \nabla.(\epsilon\vec{\tau}) + S \quad (12)$$

Where $S = -\left(\frac{\mu U_S}{K} + \beta\rho U_S^2\right)$

Thermal Modelling

Thermal modelling is done by considering the local thermal equilibrium (LTE) approach. The Local Thermal Equilibrium (LTE) model assumes a strong coupling between the solid and fluid phases within a porous media flow, enabling the estimation of a continuous temperature distribution. The governing equation for LTE is,

$$(\rho C_p)_f u\frac{\partial T}{\partial x} = k_{eff}\frac{\partial^2 T}{\partial Y^2} + \varphi_v \quad (13)$$

X= Longitudinal direction, Y= Transverse direction

$$k_{eff} = \epsilon k_f + (1-\epsilon)k_s \quad (14)$$

k_{eff} = Effective thermal conductivity, k_f = fluid thermal conductivity
k_s = Solid Thermal conductivity

Validation: Pressure drop

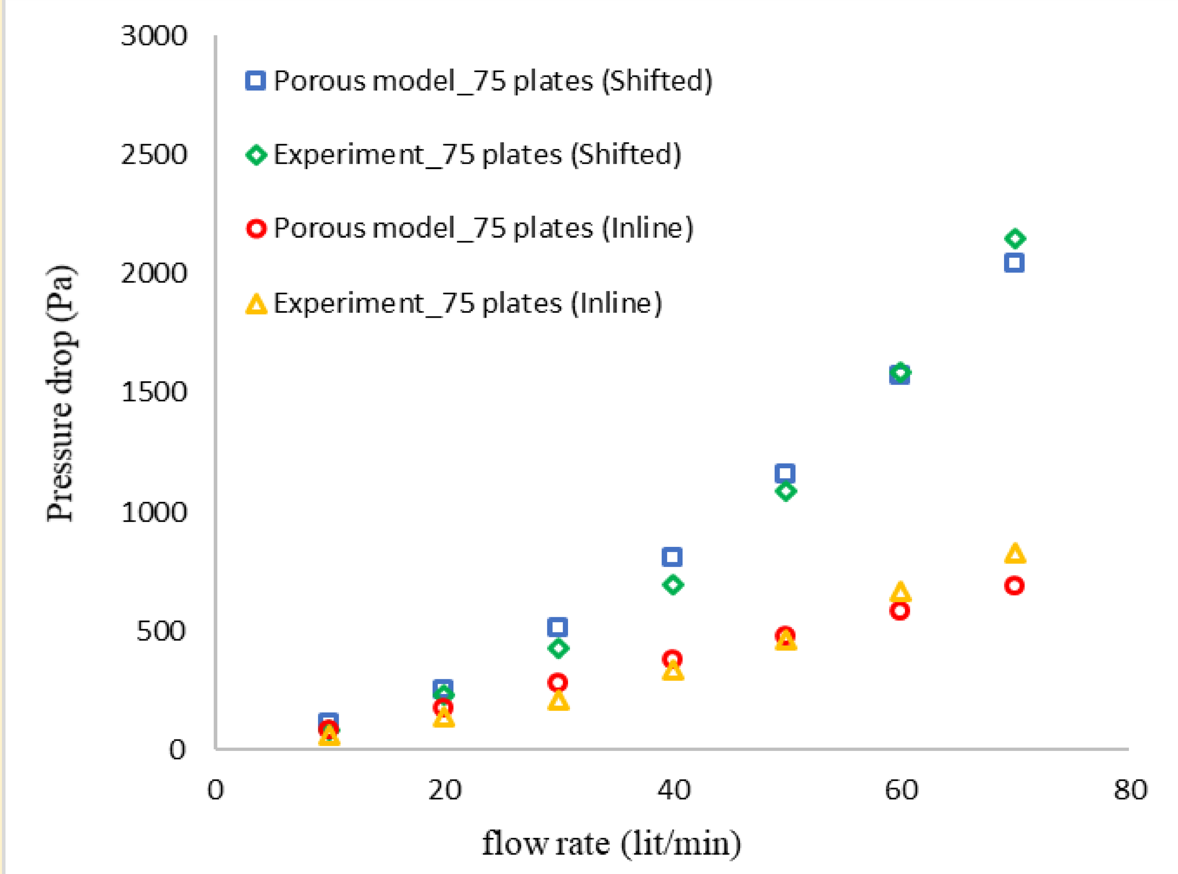

Fig. 3: Pressure drop vs flow rate for 75 Plates

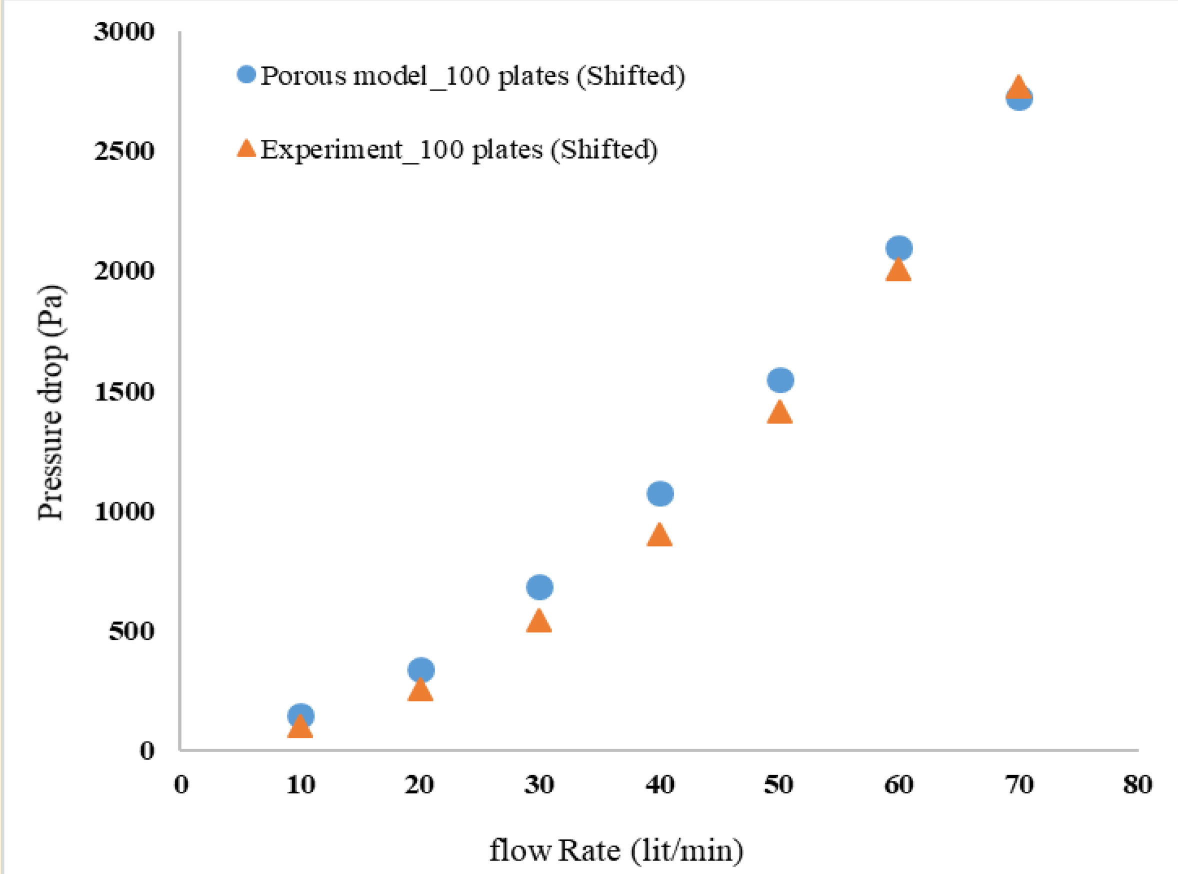

Fig. 4: Pressure drop vs flow rate for 100 Plates

Validation: The proposed model is validated through CFD simulation (using Ansys-Fluent™)of the PPHEs for which the experimental data are available [3]. The comparisons are shown in Figs. 3-7. The results on pressure drop compare within 20% of the experimental data, while in heat transfer the accuracy lies between 1 and 4 %. These demonstrate the accuracy of the proposed model. The curved profiles of pressure drops for shifted-holes indicate the influence of inertial loss because of the turbulence in the spacer region, while in the case of inline-holes, the profile is a straight line.

Validation: Heat transfer (LTE model)

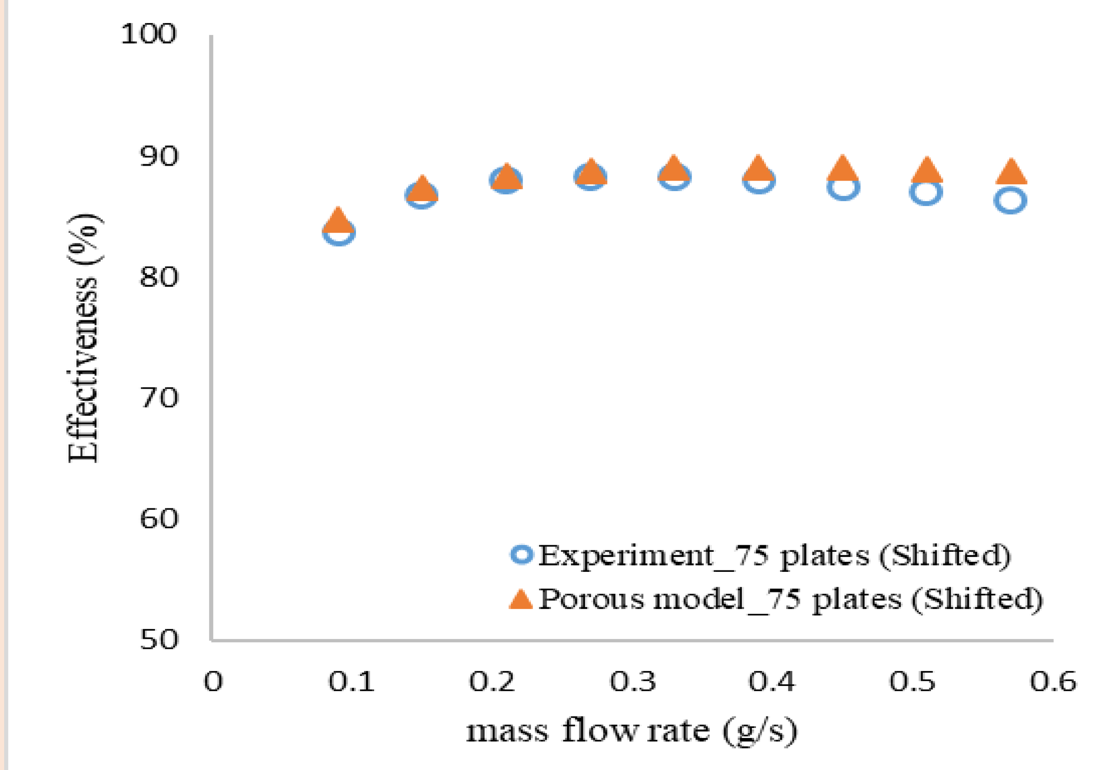

Fig. 5: Effectiveness vs mass flow rate for 75 plates

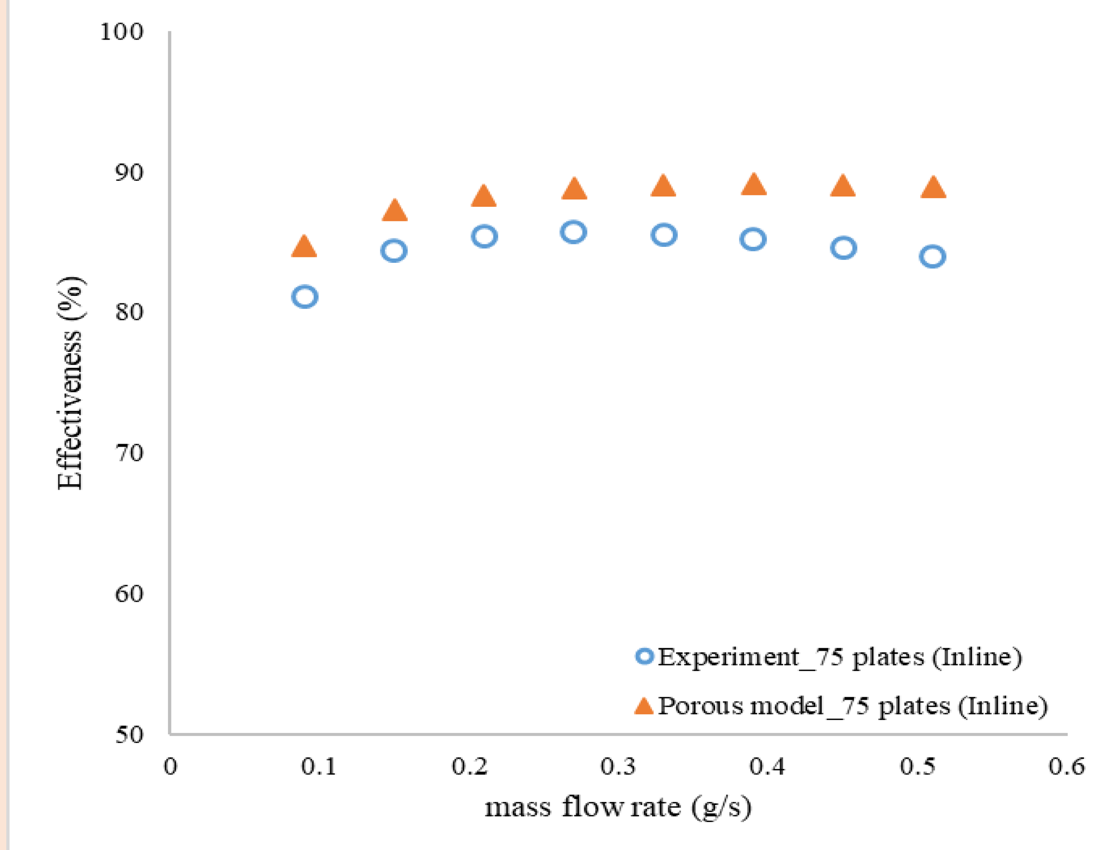

Fig. 6: Effectiveness vs mass flow rate for 75 plates

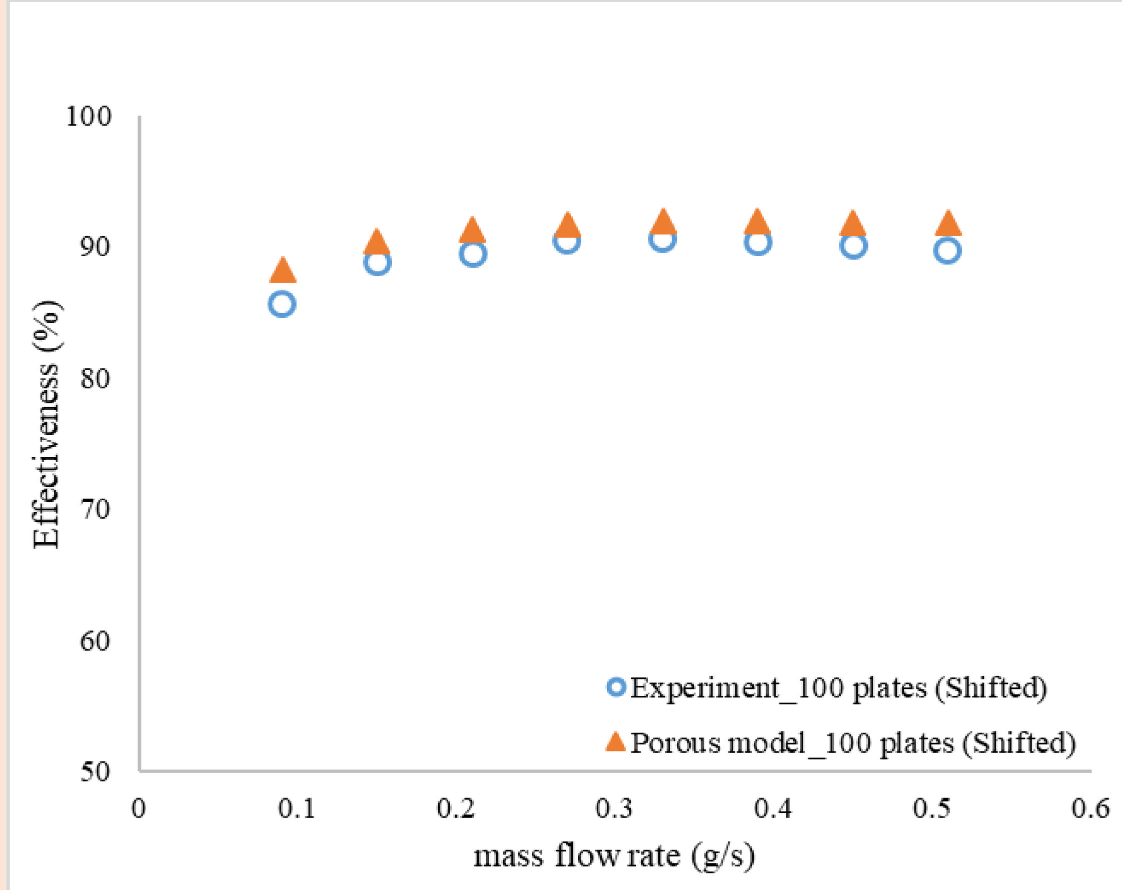

Fig. 7. Effectiveness vs mass flow rate for 100 plates

Conclusions

From this study, below are the key points that can be concluded:

1. In porous medium modelling, the Darcy-Forchheimer equation can be used to predict pressure drop efficiently.
2. Forchheimer coefficient can vary with the Reynolds number and it is not an intrinsic property of the plate.
3. Forchheimer contribution to pressure drop is more than Darcy part in the Darcy-Forchheimer equation for higher Reynolds number.
4. In the Inline hole arrangement, the spacer has very little contribution to the pressure drop. However, in the case of shifted hole arrangement, the spacer plays a significant role in the pressure drop of the heat exchanger.
5. The LTE model is found to predict results with reasonably good accuracy. However, it could be further improved by considering LTNE approach.

References

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