

Numerical and experimental investigation of bi-annulus heat exchanger for different alternative materials

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Abstract. Heat exchangers are widely used in various energy-recovery applications. However, for specific applications where metallic tubes are subjected to various drawbacks i.e. cost, weight, corrosion etc. polymer materials are promising alternatives. In present study, various conventional as well as promising alternatives materials are chosen for investigation computationally. Experimentally, bi-annulus heat exchanger configuration is investigated for metallic materials. The simulations carried out conclude that the dimensionless temperature parameter for Cross-linked polypropylene (PEX) is greater than other polymers. It increases with increasing axial length of tube. The value for dimensionless temperature is higher for copper which is used as conventional tube material. Among different polymers highest temperature is observed for PEX followed by Low density polypropylene (LDPE), Polypropylene (PP) and Polyvinylidene fluoride (PVDF). For axial length up to 70mm approx. the temperature rises for PEX, LDPE is 28.3% and 26.4% respectively. However, temperature variation is same for PP and PVDF for same axial distance. This temperature variation is increased to 72.4%, 67.2%, 58.62% and 56.89% for PEX, LDPE, PP and PVDF respectively as axial distance variation reaches the end of pipe. The inner annulus temperature for PEX material at 10% length of tube is 28.3% of temperature achieved in copper tube which increases to 72.4% for full length of tube.

1. Introduction

In almost every heat transfer or energy-recovery application, heat exchangers are prominent to overall efficiency, cost and size of system. Presently, these applications (air-conditioning, refrigeration etc.) are based on fin-tube, plate-fin heat exchanger designs constructed using copper, aluminium. There is vast literature present whether how to enhance the heat transfer. However, the operating temperature is a limitation for metallic heat exchangers. Especially for applications like heat recovery where solvent is corrosive and exotic alloys are required. Hence, polymers solve the purpose being a) flexible in manufacturing b) chemically stable c) reduced cost as well as weight. These find application in chemical industry as well as liquid to liquid, gas to gas along with liquid to gas application [1][2]. Various applications for liquid to liquid configuration have been explored and investigated [3][4] citing the advantages with respect to corrosion resistance and weight cost factor. Moreover, triple tube or bi-annulus heat exchanger basically suited for pasteurization, drying, sterilizing, cooling, freezing, refrigeration and evaporation. Theoretical analysis had been performed relating the performance of heat exchanger with size of triple pipe [5][6]. Effectiveness equation as well as mathematical formulation for heat transfer coefficient was also developed [7]. Correlations for partial coefficient was also developed [8]. The effectiveness as well as advantages of triple pipe heat exchanger is given



in review [9] as well as method of calculating heat transfer coefficient and mean temperature difference has been provided [10,11].

The application of polymers specific to triple pipe heat exchanger or bi-annulus heat transfer device is rarely discussed. This present paper deals with the material of heat exchangers particular to polymers. In order to investigate an experimental study is also carried out and numerically different parameters are varied to obtain temperature, pressure profiles. Ansys WorkBench[12] module is chosen to investigate the problem numerically. Different materials are chosen for thermal analysis namely Copper (Cu), Aluminium (Al), Steel, PP, PEX, Low density polypropylene LDPE, PVDF for numerical analysis.

2. Brief experimental details

The experimental setup consists of several components depending on the required functioning for the practical work. The components used in this experiment are Rotameter, DC water pump, Temperature Sensors, Gate valve. The temperature sensor used to calibrate the inlet and outlet temperatures of the heat exchanger in this experiment is LM35. It is a precision integrated circuit temperature device. These temperature sensors calibrate directly in Celsius with $+10\text{mv}/^{\circ}\text{C}$ scale factor and 0.5°C ensured accuracy at 25°C . The range of the temperature sensor varies between -55°C to 150°C . These sensors operate from 4V to 30V with current drain less than $60\mu\text{A}$. LM35 temperature sensors are easily available at the markets at affordable cost and very suitable for remote applications. The setup consists of three pipes which are in concentric arrangement made up of copper. These pipes are namely center pipe, intermediate pipe and outer pipe. Single inlet is provided to both the center pipe and the outer pipe through with cold fluid flows with an equal mass flow rate in both the pipes. Hot fluid is made to flow in the intermediate pipe. Panel Mount Rotameter is placed before both the inlets to control the flow rate of the fluid. A ball valve is placed for the inlet of the outer pipe where this valve plays a major role in showing the dual mode compatibility of the heat exchanger. If this valve is closed it acts as a Double Pipe Heat Exchanger and when it is open it acts as a Bi-annulus Heat exchanger. The results one can depict that in comparison to conventional double pipe heat exchanger heat transfer per unit length, thermal efficiency and heat flux have improved. Heat transfer length has decreased from 1.369m to 0.447m in comparison of Double pipe heat exchanger to Bi-annulus heat exchanger. The flow observed in the pipes are found to be laminar for provided volumetric flow rates. Achievement of turbulent flow can enhance the heat transfer rate and can increase thermal efficiency. The results obtained from experimental result is presented in table 1 where U being overall heat transfer coefficient and L being length of heat exchanger. The outer average static temperature obtained from experimental result (49°C) as well as numerical simulation (48°C) is well in conformation.

Table 1. Experimental results.

Material	U ($\text{W}/\text{m}^2\text{K}$)	L (m)
Copper	197.28	0.44
GI (Stainless Steel)	193.41	0.45
GI (Mild Steel)	195.98	0.44

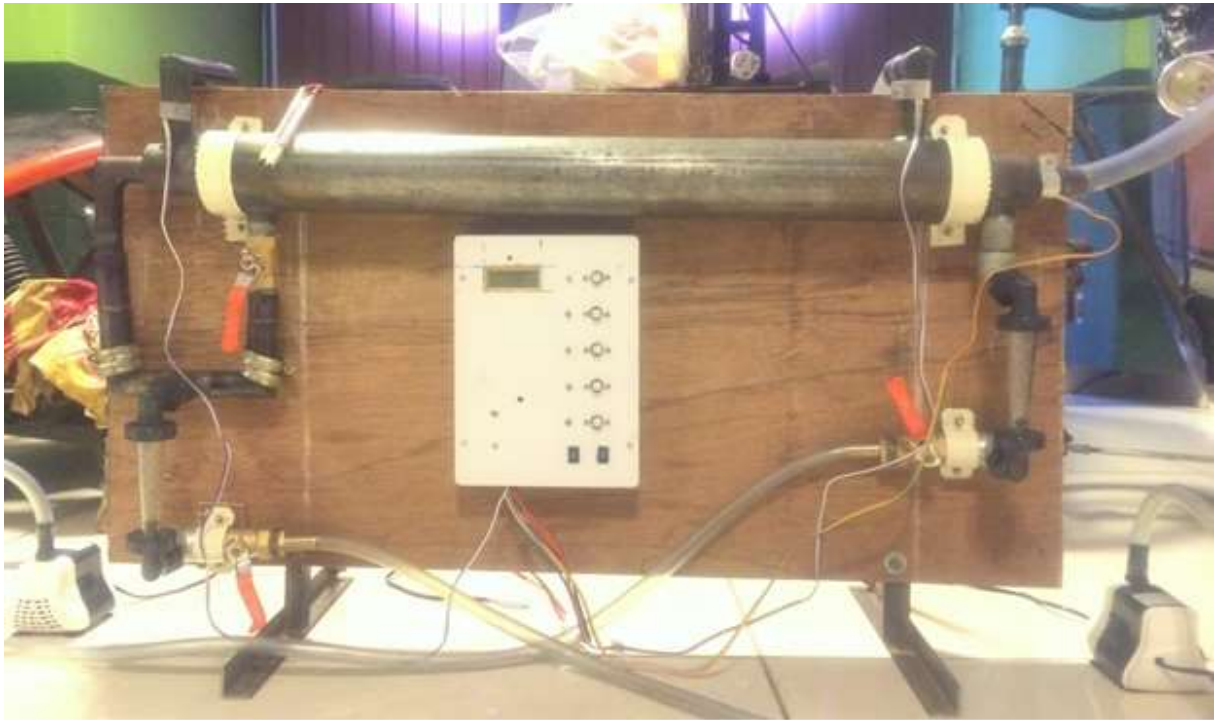


Figure 1. Experimental setup for bi-annulus heat exchanger.

3. Numerical Procedure

3.1. Mathematical model

The problem is formulated in two dimensions considering axis (700mm) as symmetric in order to reduce time and computational cost. The sketch is shown in figure 2. The problem is thermally analysed taking into consideration some of the assumptions as a) steady state operation b) no heat sink or heat source c) mass flow rate remains constant d) all the properties and parameters along with variables are considered constant. Since, the flow for all the three fluids is in same direction hence it is a co-current flow arrangement of heat exchanger. The governing equation for different fluid streams are

$$(\dot{m}C_p)_h \frac{dT_h}{dx} = (U_2P_2 + U_1P_1)(T_h - T_c) \quad (1)$$

$$(\dot{m}C_p)_c \frac{dT_c}{dx} = U_2P_2(T_h - T_c) + U_0P_0(T_\infty - T_c) \quad (2)$$

Further different non-dimensional parameters are used to plot temperature variation as follows:

$$\theta = \frac{T - T_{c,in}}{T_{h,in} - T_{c,in}} \quad (3)$$

$$X = \frac{x}{L_e} \quad (4)$$

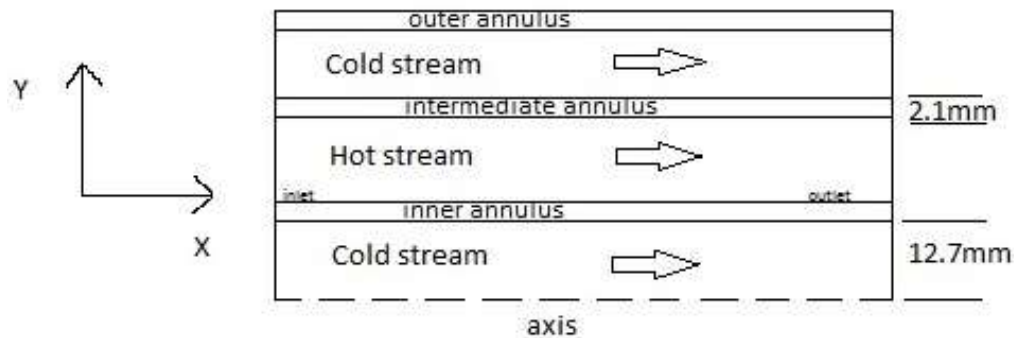


Figure 2. Two dimensional sketch of bi-annulus heat exchanger

3.2. Numerical scheme and boundary conditions

Since, water is chosen as the fluid flowing in the bi-annulus heat exchanger. Hence, the flow was laminar, therefore laminar model is invoked. The simulation for laminar flow are carried out using FLUENT 15 software package. Second order upwind scheme is used for discretization of pressure velocity coupling equations. For residuals of continuity and momentum equations, a convergence criterion of 10^{-3} was imposed whereas 10^{-6} as energy equation residuals. The convergence is determined by the residual levels and also by monitoring relevant integrated quantity like heat transfer coefficient. The solutions are obtained only after satisfying convergence criterion. The boundary conditions to which are inlet temperature of fluid for cold fluid the inlet temperature being 298K and for hot stream of fluid being 328K with 0.01388 kg/s and 0.0277 kg/s as flow rates. The outer wall of heat exchanger is considered to be insulated that is no heat is transferred from the outermost wall.

3.3. Mesh description

Two dimensional model is meshed with structured mesh. Since, structured mesh reduces errors considerably. Four different grid sizes are chosen in order to check the independency of grid, with the solution of numerical procedure. The grid chosen consist of 81,650 elements out of the numerically analyzed grid consisting elements ranging from 14,353 to 81,650. The grid independence study is given in table 2. Since, percentage deviation is less than or equal to unity for 81,650 element grid, it is chosen for further investigation. The grid size is further validated according to criteria present in literature [13]. The maximum skewness value for the generated mesh being 0.052 which should not exceed 0.85 as well as the orthogonal quality 0.99 which is close to unity providing the quality mesh for numerical procedure. The obtained mesh is shown in figure 3.

Table 2. Grid independence study.

Elements	Nusselt Number (Nu)	% deviation
14353.00	7.50	
26562.00	8.08	7.73
57750.00	8.40	3.95
81650.00	8.49	1.06

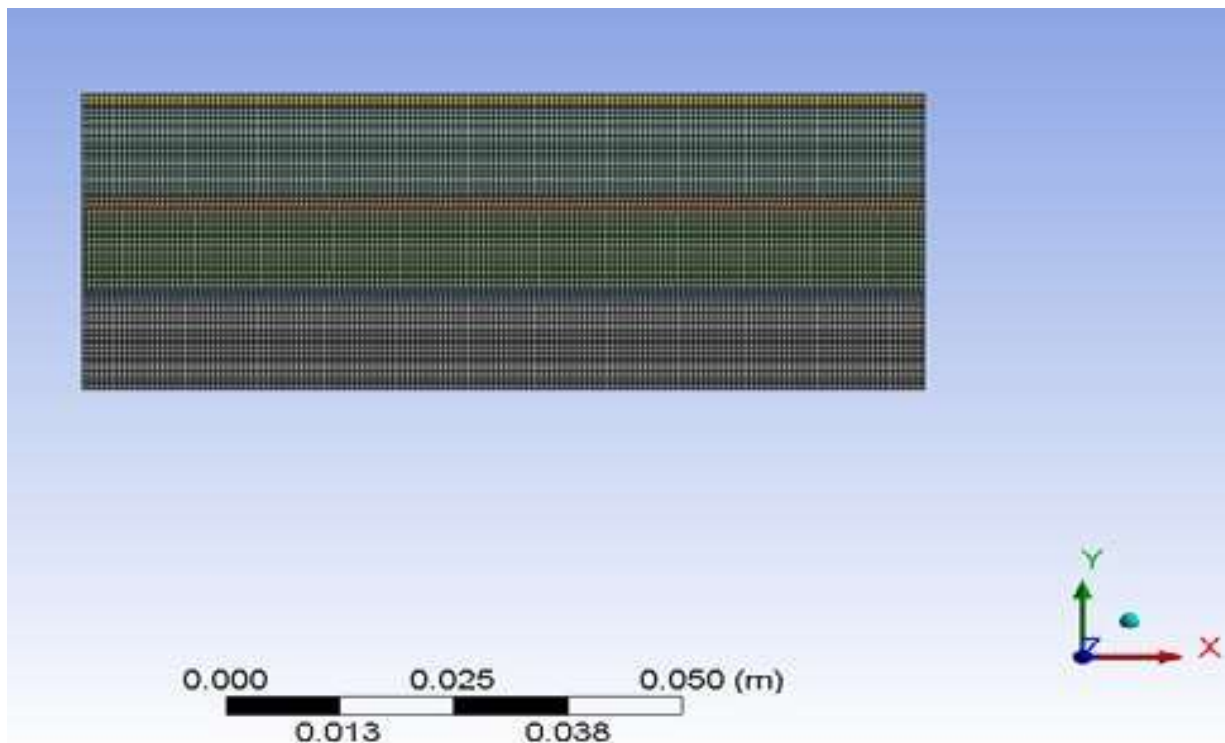


Figure 3. Two dimensional sketch of bi-annulus heat exchanger

4. Results

4.1. Isotherm

Bi-annulus heat exchanger temperature profile can be seen as isotherms considering different polymer materials as well as different metals that are conventionally used in heat exchanger application. It can be easily differentiated that as compared to metal counterpart's polymer pipes are at lower temperature. However, the difference in profile is almost negligible. Hence, it poses a promising material for heat exchanger application in chemical industry.

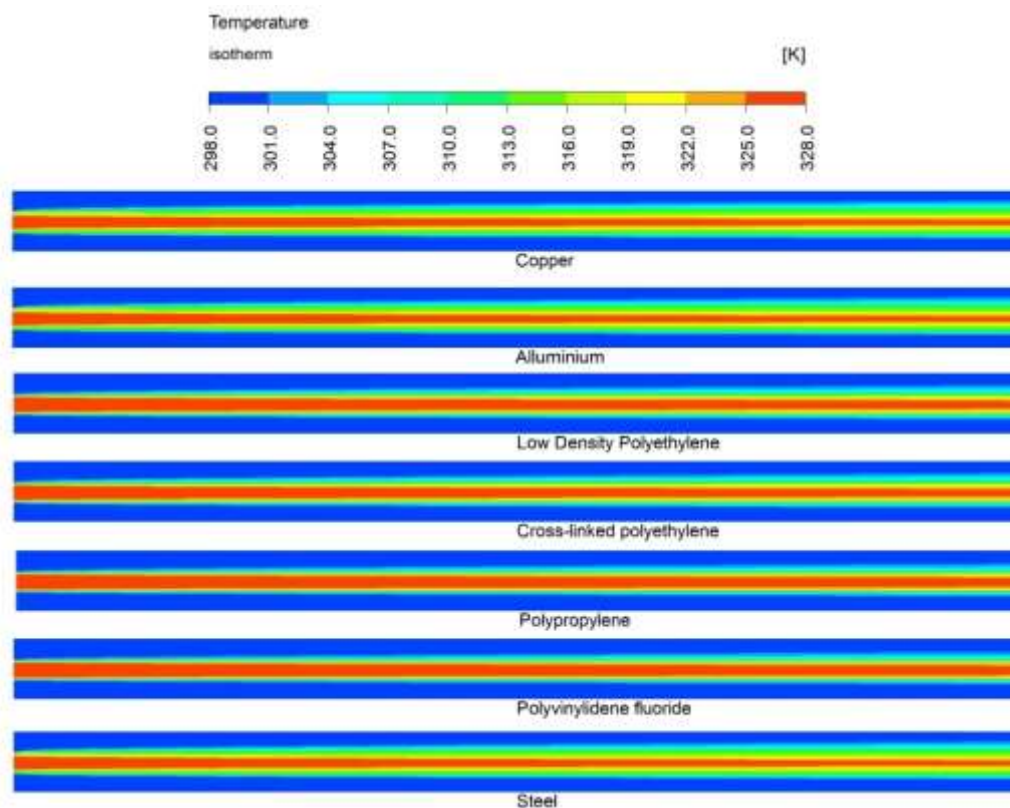


Figure 4. Isotherm contours for different material of bi-annulus heat exchanger pipes.

4.2. Heat Transfer

The temperature variation along the length of heat exchanger tube is shown in figure 5. The dimensionless temperature for PEX is greater than other polymers. It increases with increasing axial length of tube. The value for dimensionless temperature is higher for copper which is used as conventional tube material. Among different polymers highest temperature is observed for PEX followed by LDPE, PP and PVDF. For axial length up to 70mm approx. the temperature rises for PEX, LDPE is 28.3% and 26.4% respectively. However, temperature variation is same for PP and PVDF for same axial distance. This temperature variation is increased to 72.4%, 67.2%, 58.62% and 56.89% for PEX, LDPE, PP and PVDF respectively as axial distance variation reaches the end of pipe. From figure 6, it can be concluded that PEX having highest temperature rise among all polymers is compared with conventional copper material. The inner annulus temperature for PEX material at 10% length of tube is 28.3% of temperature achieved in copper tube which increases to 72.4% for full length of tube. Similarly, this variation for intermediate annulus of copper increases from 70.9% to 88.05% of PEX material. For outer annulus the variation is almost negligible for both copper as well as PEX polymer material. However, this is increased to 75% of copper temperature rise for full length of tube.

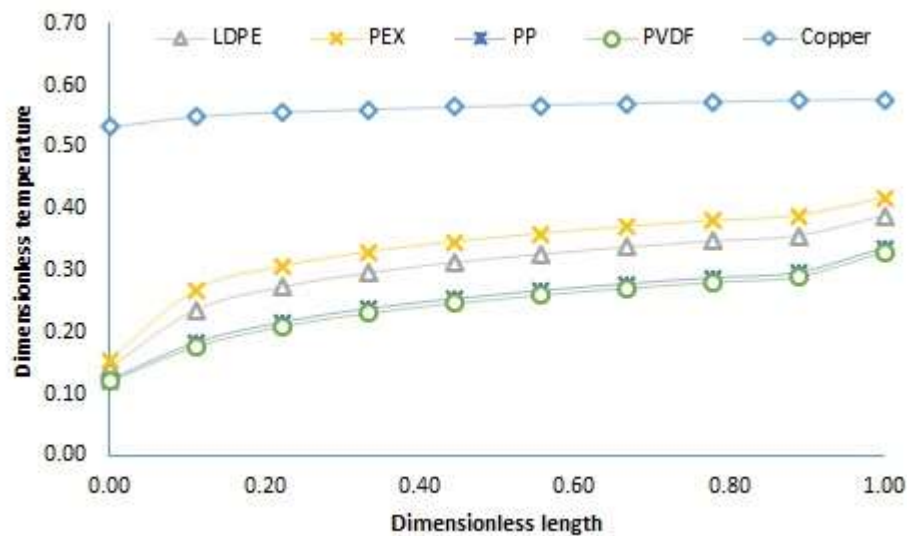


Figure 5. Dimensionless temperature variation along axial direction.

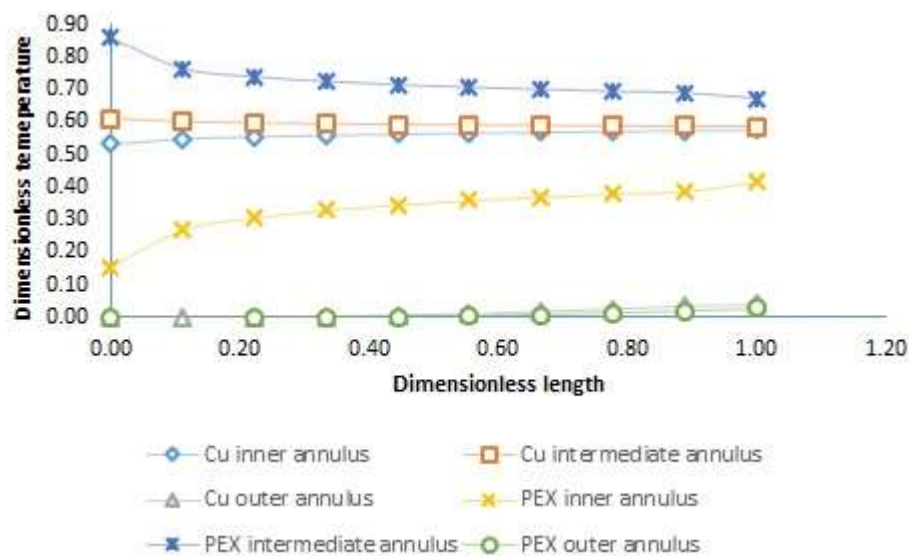


Figure 6. Comparison of different annulus walls for Copper and PEX.

5. Conclusions

Bi-annulus heat exchanger is investigated experimentally as well as numerically. The simulations are carried out for different polymer materials along with conventional tube materials mainly metal. It is concluded that the dimensionless temperature for PEX is greater than other polymers. It increases with increasing axial length of tube. The value for dimensionless temperature is higher for copper which is used as conventional tube material. Among different polymers highest temperature is observed for PEX followed by LDPE, PP and PVDF. For axial length up to 70mm approx. the temperature rises for

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6. References

- [1] Zaheed L and Jachuck R J J 2004 Review of polymer compact heat exchangers, with special emphasis on a polymer film unit *Appl. Therm. Eng.* **24** 2323–58
- [2] Reay D A 1989 The use of polymers in heat exchangers *Heat Recover. Syst. CHP* **9** 209–16
- [3] Zarkadas D M, Li B and Sirkar K K 2005 Polymeric hollow fiber heat exchangers (PHFHEs): A new type of compact heat exchanger for lower temperature applications *ASME 2005 Summer Heat Transfer Conference collocated with the ASME 2005 Pacific Rim Technical Conference and Exhibition on Integration and Packaging of MEMS, NEMS, and Electronic Systems* (American Society of Mechanical Engineers) pp 429–38
- [4] Liu W, Davidson J and Mantell S 2000 Thermal analysis of polymer heat exchangers for solar water heating: a case study *Trans. Soc. Mech. Eng. J. Sol. ENERGY Eng.* **122** 84–91
- [5] Ünal A 1998 Theoretical analysis of triple concentric-tube heat exchangers Part 1: Mathematical modelling *Int. Commun. heat mass Transf.* **25** 949–58
- [6] Ünal A 2001 Theoretical analysis of triple concentric-tube heat exchangers Part 2: Case studies *Int. Commun. heat mass Transf.* **28** 243–56
- [7] Ünal A 2003 Effectiveness-NTU relations for triple concentric-tube heat exchanges *Int. Commun. heat mass Transf.* **30** 261–72
- [8] Radulescu S, Negoita I L and Onutu I 2012 Heat transfer coefficient solver for a triple concentric-tube heat exchanger in transition regime *Rev Chim* **8** 820–4
- [9] Zuritz C A 1990 On the design of triple concentric-tube heat exchangers *J. Food Process Eng.* **12** 113–30
- [10] Batmaz E 2003 Overall heat transfer coefficients and axial temperature distribution of fluids in a triple tube heat exchanger
- [11] Batmaz E and Sandeep K P 2008 Overall heat transfer coefficients and axial temperature distribution in a triple tube heat exchanger *J. Food Process Eng.* **31** 260–79
- [12] ANSYS 2013a 2013 Ansys Fluent Help
- [13] Bakker A 2013 Lecture 7 – Meshing *Applied Computational Fluid Dynamics*