IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
Volume 2, Issue 7, June 2022
Impact Factor: 6.252

Heat Exchanger Design with Supercritical Fluid

Anurag Warghat[1], Shanteshwar Dhanure[2], Mohit Surwade[3], Krishan Pandey[4], Chetan Chimote[5]
Lecturer, Department of Mechanical Engineering[1,2,3,4,5]
Pimpri Chinchwad Polytechnic, Pune, Maharashtra, India

Abstract: *Supercritical fluids are utilised to improve the thermal performance of various heat exchangers all over the world, and their use in power cycles in thermal power plants is also being studied. These fluids boost the ability of low-grade energies, such as heat energy, to be used more effectively. Before beginning the study, various fluids were considered. CO2 is being considered by a number of studies. To make brayton cycles apps perform better. Simulations were run with isobutane as the supercritical fluid in this investigation. The thermal performance of printed type heat exchanger channels in counter flow configurations was calculated. Isobutane was discovered to be a better option to CO_2 as a working fluid in heat exchangers.*

Keywords: Supercritical Fluid, Heat Exchangers, Isobutene, Heat Exchangers, etc.

I. INTRODUCTION

A supercritical fluid is one that has passed its critical temperature and pressure threshold and cannot be distinguished into gaseous and liquid phases. These fluids can emit through solids such as gas or dissolve in materials such as liquids. Researchers originally discovered supercritical fluids while conducting an experiment involving the sound of a flint ball in a fully covered canon. Heat exchangers use supercritical fluids because they have low viscosity, high density, and increased thermal conductivity. When a fluid approaches its critical point, minute changes in its pressure and temperature occur, causing impacts on the density and allowing different properties to be tuned.

The efficiency and compactness of power cycles involving these fluids are extremely high. They're getting more popular these days because they can be used for both nuclear and solar energy. Water and steam are employed as running fluids in modern turbine power plants, and fluids at supercritical stages use fluids with pressure and temperature above critical point. It has the ability to adopt attributes in the middle of the power cycle, resulting in increased usage and higher efficiency over the entire power cycle. Because the density of a fluid increases in its supercritical state, the space occupied by turbines and other components in a powerplant is reduced, resulting in a small plant with cheap costs. The use of supercritical fluid improves a power plant's efficiency and a heat exchanger's performance, allowing low-grade energy to be efficiently utilised.

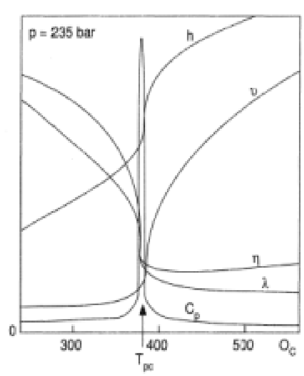

Figure 1: Pseudo critical temperature point

When the thermal characteristics of a fluid are enhanced above their critical point, the main dissimilarity develops in its operation. Dissimilarity occurs along the saturation line and the x-direction pressure line of the constant temperature line, where distinct phases of water are involved in changing their quantity. The constant temperature line has no slope at a point on the curve where the pressure is critical, pc. When the fluid temperature exceeds its critical temperature, the constant temperature line does not become discontinuous, and supercritical qualities are obtained. After passing through the critical point of a fluid, a stage occurs where the specific heat of the fluid increases dramatically before decreasing; this point is known as the pseudo critical point of the fluid. Heat exchangers are commonly employed in power plants as a recuperator and regenerator, with increased efficiency and performance resulting in increased stability.

Above the critical point, many investigations on the use of carbon dioxide as a fluid in the heat exchanger are underway. People studying choose carbon dioxide as a heat exchanger fluid because of its low critical point (31C, 7.4Mpa)Plate heat exchangers and double tube heat exchangers are being studied as a recuperator in thermal power plants all over the world. Researchers, on the other hand, are more interested in the Printed Circuit kind. These are a novel type of heat exchanger that features high-efficiency microchannel vaporizers and is densely packed. As a result, they are the centre of attention. Photochemical etching and diffusion bonding were used to create this micro-channel heat exchanger. As a result, when compared to its other varieties, PCHE performs better. PCHE has a number of disadvantages, one of which being pressure drop. As a result, experts have been researching and developing methods to increase its functionality.

Fluid Selection

The selection of fluid was done depending upon their properties. Many fluids had adverse environmental effects. Also, many fluids which had not shown harmful environment effect had high critical point. This means that it would be practically difficult to achieve those operating conditions.

Fluid	Critical properties	Other Properties
R134a	(4.06Mpa,374.01K)	High GWP, Displace oxygen, low toxic
R227ea	(2.92Mpa,374.75K)	High GWP, low heat of vapourisation
R245fa	(3.65Mpa,427.01K)	Zero ODP, high heat transfer performance
R410a	(4.86Mpa,72.8C)	High GWP, volatile, nonflammable,
R290	(4.25Mpa,96.7C)	Natural refrigerant, low GWP
R600a	(3.64Mpa,134.71C)	Zero ODP, low GWP, high energy efficiency
R32	(5.78Mpa,78.105C)	Low GWP, high energy efficiency, less flammable

Among these fluids, the fluid selected was R600a also known as isobutane because of its low environmental impact.

II. LITERATURE REVIEW

Matteo Marchionni et. al (2019): The modelling of the PCHE type of heat exchanger was carried out. The heat exchanger was used as a recuperator in power changing systems. The scope of the lower order models in finding the total heat transfer and performance were studied. The PCHE channels were studied using 1D as well as 3D modelling using ansys software, heat transfer channels were. This study found out that the significance of the 1D modelling can be used in assessing the performance of the heat exchanger. The difference between the results of 1D and 3D modelling was found to be only of 2% thus 1D modelling can be useful in assessing its thermal performance, thus using this simulation time can significantly reduce. Unsteady state analysis was done.

Young-Jin Baik et. al. (2017): The performance of another type of heat exchanger which have wavy shaped channels were studied. The waviness factors of amplitude as well as period on its functioning were studied numerically with the help of ansys. on the PCHE were studied numerically. The comparison was done of wavy channelled heat exchanger to the straight channelled heat exchanger. After calculating the results numerically, it was found out that the performance of wavy channelled heat exchanger was greater than that of straight channelled by 16.4%. The thermal performance of wavychanneled PCHEs monotonically increases as either of the amplitude or period increases. The channel size has not any considerable impact on the thermal performance than the waviness amplitude and period. The thermal performance per unit period increases as the amplitude increases. However, it decreases as the period increases.

Amjad Farah et. al.(2016): Study of a CFD code as well as the capabilities of FLUENT code were determined. The study was done on the tubes with fluid flowing vertically. Water was used as a supercritical fluid in this study. Prediction of the wall temperature was done in the tubes. The simulations were carried out using FLUENT solver. Working fluid was water. The calculations were done by 1D modelling and the results of which were compared with existing corelations. Calculations were carried out using k-ε as well as k-ω turbulent models in the pseudocritical region. Study found out that there was an error of 10% in the values of wall temperature when calculated using k-ω model and of 5% in deterioted heat transfer area and normal heat transfer area respectively. Thus, it was found out that the of model had higher accuracy as compared of any earlier tested corelation.

Muhammad Saeed et. al. (2019): The study was carried out on PCHE type of heat exchanger; the channels were of sinusoidal in shape. In this study, the thermal as well as hydraulic performance were carried out, a new type of channel shape was proposed. The comparison of zig-zag channel as well as staggered arrangement was done. The working fluid used was CO2. Response Surface Methodology (RSM) was used to optimize the channel geometry combined with the help of genetic algorithm. At last, thermal as well as hydraulic study were carried out numerically with different values of reynolds number. After this pressure drop and heat transfer correlations were suggested. After calculating the results, it was found out that the sinusoidal shaped channel was showing 2.5 times better performance as compared to zigzag shaped channel. The thermal performance on the cold side and hot side were 21% and 16% better respectively.

Zhongchao Zhao et. at. (2017): In this study, heat transfer as well flow analysis was done. Airfoil fins on PCHE were present. The fluid was liquified natural gas. The characteristics on LNG on the PCHE having airfoil fins depending upon its arrangement was numerically found out. Comparison of straight channelled and airfoil fin were carried out. Effect of staggered pitch and vertical pitch were studied. Discontinuous fins, airfoil fin can increase the thermal performance of PCHE. The arrangement of the staggered fins was more advantageous as compared to the parallel fins. Study found out that the velocity was increased of the supercritical fluid in the fin shaped geometry and then gradually decreased as the vertical pitch was increasing.

Yimeng Zhou et. al. (2019): Thermal and hydraulic performance was determined of the PCHE. The channel was zigzag shaped. The PCHE type of heat exchanger was used for higher pressure as well as for vapourization for vapourizers. The thermal as well as hydraulic analysis was done in PCHE with zigzag shaped channels numerically. SST k-w model was used. Piecewise polynomial approximations were used to find out thermal as well as physical properties. Properties such as bend angle, inlet pressure, mass flow rate were studied. Their effects on heat transfer coefficient and pressure drop were also studied. Nu and Eu numbers were useful to determine heat transfer as well as pressure drop. It was found that the HTC was increasing and then decreasing along the direction of the stream. The highest value was found near pseudo critical point. As bend angle was increased the pressure drop was also increasing. The local convective heat transfer increases when temperature surpasses pseudo critical point, but changes little with inlet pressure before pseudo critical point.

Jingzhexie et. al (2018): In this study, prediction of supercritical fluid on the heat transfer properties was carried out. The circular tube was used for prediction in crossflow fluid channels. To avoid the studies on circular tubes geometries, studies on pressure at supercritical stage was carried out. The main focus of the study was on the experiments done on different fluids like water, n-decane, etc. their review and study their results. Also, focus of the study was flow across shell and tube type of heat exchangers. These heat exchnagerstye can be used for power cycle systems. The study was carried out for cross flows. In this study, it was found out that heat transfer was 9 significantly depended on the heat flux like it was in in-tube flows. There was a unique feature in thermal as well as physical properties as the boundary conditions changed.

SangwooJeon et. al. (2016): The study was carried out on heterogenous types of printed circuit heat exchanger. The working fluid was carbon dioxide. The proposal of using heterogenous PCHE was suggested and calculation activities was done to determine its performance. Various parameters were considered to check thermal performance, they were variation in the size of channels at the inlet and outlet, the channel space variations. Change in cross section of channels was also done. It was found out that when the channel size was increased its thermal performance was decreasing. This was because of decrease in the flow rate. The thermal characteristics were unaffected by variation of channel size, but it had reduced the structural reliability of the PCHE. The thermal performance was similar for same hydraulic diameter.

Despite there being studies on supercritical fluid, no significant improvement in heat transfer have been found out. The high pressure drop performance were found to be in printed circuit heat exchangers having S shaped as well as others having Air foil fins. In comparison the ZigZag type PCHE flow channels had low pressure drop performance. It was found that these channel with discontinuous fins are not durable under high pressure. Thus increasing the manufacturing and maintenance costs of the heat exchanger. Therefore, it is necessary to study on the continuous channels and their shapes and sizes can be varied.

III. MATERIALS AND METHODOLOGY

Ansys 14.5 Fluent solver was used for the analysis of the PCHE channel. A channel design geometry was of 3mm×4mm with 160mm channel length. The hydraulic diameter of both cold channel and hot channel was taken as 1.5mm.

The hydraulic diameter of a semi-circular channel is

$$D_H = \frac{D}{1 + \frac{2}{\pi}}$$

Where, D_H = Hydraulic diameter

D = channel diameter

The channel diameter of both hot and cold fluid was 2.454mm.

Table 2: Properties of isobutane

Thermal Conductivity(kg/mk)	0.0159
Density(kg/m^3)	2.46
Viscosity(Kg/ms)	7×10^{-6}
Specific heat(J/kgk)	2620

Table 3: Properties of Methane

Thermal Conductivity(kg/mk)	0.0332
Density(kg/m^3)	0.6679
Viscosity(Kg/ms)	1.087×10^{-5}
Specific heat(J/kgk)	4110

Table 4: Properties of steel

Density(kg/m^3)	8030
Specific heat(J/kgk)	502.48
Thermal conductivity(kg/mk)	16.27
Thermal conductivity(kg/mk)	8330000

IV. GEOMETRY

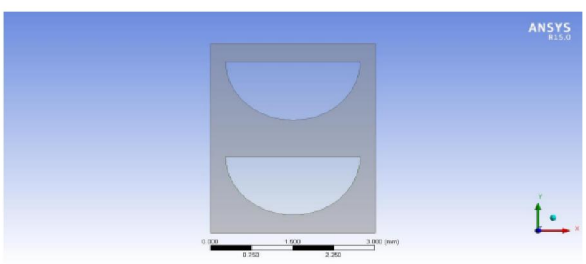

Figure2: Front view

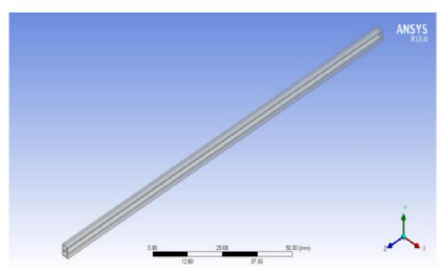

Figure 3: Isometric view

The geometry was made in the ansys software. For drawing geometry at first units of software were set in mm. a sketch of the geometry incluing that of flow channels was drawn on the in the x-y plane. Extrude command was applied in the z direction for 160mm. After this the fluid domain was made using the 'Fill' tool on using selecting the inside channels of both hot and cold fluids. The parts were renamed using appropriate names. All the bodies were grouped and formed a new part.

IJARSCT
ISSN (Online) 2581-9429
International Journal of Advanced Research in Science, Communication and Technology (IJARSCT)
Impact Factor: 6.252
Volume 2, Issue 7, June 2022

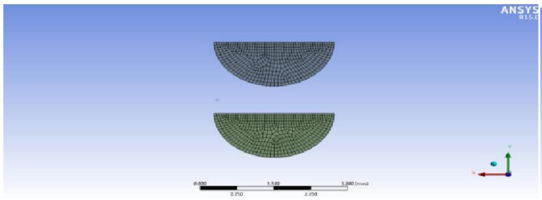

Figure 4: Meshing of fluid channels

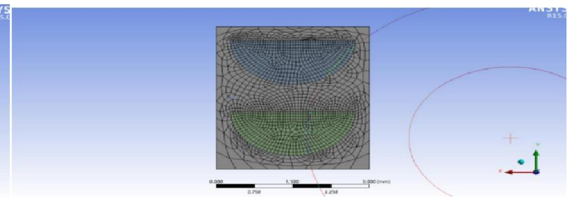

Figure 5: Meshing of surface

V. SETUP

In the setup mesh was checked. Units were set, absolute pressure-based model was selected for incompressible flow calculations. Steady state was selected. Gravity in y direction was set at -9.81m/s2. Energy equation was set on in the model tab. It is known that than k-ε turbulence model predicts the pressure drop by 30% below under the experiments carried out by Val Abel, thus SST k-ω turbulance model was applied while simulation. Materials were selected from the database which were water, isobutane and steel. Cell zone boundary condition were given to body, cold and hot fluid.

Boundary conditions of the inlet of both the fluid were mass flow rate inlet where cold fluid enters the domain at 1.95kg/s and hot fluid enters at 1.95kg/s. the cold fluid enters at 239C, 136 bar and leaves considering the fluid remains in the supercritical state all the way. The hot fluid enters at 650C, 1.06 bar. The outlet conditions of both the fluid were set as pressure outlet. The pressure and velocity were coupled using the SIMPLEC algorithm. The spatial discretization least square based gradient was selected whereas the pressure and momentum using second order upwind method, whereas turbulent kinetic energy, specific dissipation rate using first upwind. Standard initialization was done and the solution was initialised all zones. The values of mass flow rate were varied and were 1.8kg/s and 2.1kg/s on both sides. The solution was converging in nearly 100 to 110 iterations for all cases.

VI. RESULTS

Simulations were carried out to calculate the effect of mass flow rate on the thermal properties of the heat exchanger, the mass flow rate of both the fluids was 1.95kg/s. Below is the temperature profile of the fluid at zone 1, which was of cold outlet and hot inlet. The value of the various parameterswere can be found in Reports section in the setup menu.

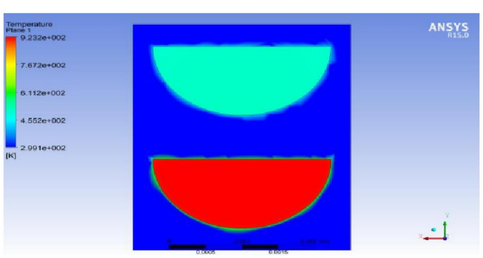

Figure 7: Temperature profile at zone 1

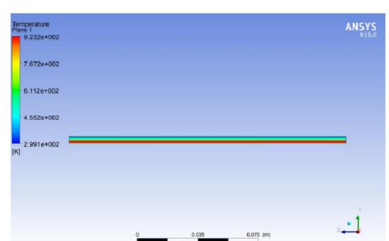

Figure 8: Temperature profile

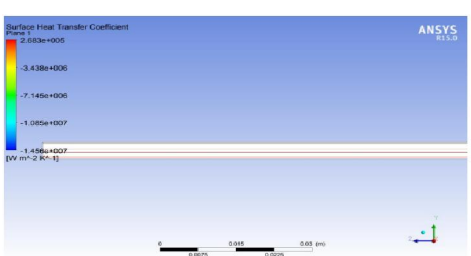

Figure 9: Surface heat transfer coefficient

Figure 10: surface nusselt number

Effect of mass flow rate of 1.95kg/s on heat exchanger

After simulation, we have now known the outlet temperature of both fluids

Let Th_1 and Tc1 be inlet temperature of both the fluids and Th2 and Tc2 be outlet temperature of both fluids. The values came out to be:

$Th_2 = 483C$, $Tc_2 = 501C$ The total heat transfer rate can be calculated with the help of

$Q = m_h.C_{ph}\times(Th_1\text{-}Th_2) = m_c.C_{pc}\times(Tc_2\text{-}Tc_1) = 1340KW$

To calculate the effectiveness, we have

$$\varepsilon = \frac{Q}{Q_{max}}$$

$Q_{max} = C_h\times(Th_1\text{-}Tc_1)= C_c\times(Th_1\text{-}T_{c1})$ whichever is lower among these two values

$C_h = m_h.C_{ph} = 3293KW$

$C_c = m_c.C_{pc} = 2101KW$

Therefore, effectiveness came out to be 63%

Effect of mass flow rate of 2.1kg/s

The outlet values were found to be

$Th_2 = 472^0C$, $Tc_2 = 517^0C$

Total heat transfer rate

Q = 1530KW

$\varepsilon = 72\%$

Effect of mass flow rate of 1.8kg/s

Q = 1190KW

$Th2 = 489^0C$, $Tc2 = 491^0C$

Q = 56%

VII. CONCLUSION

Isobutane have found to be among the other alternative than CO2 against as a working fluid in thermal power plant which run supercritical cycle. The outlet conditions were calculated using CFD. Effects of mass flow rate on the thermal performance were also determined. It was found that the effectiveness increased with increase in mass flow rate. Heat transfer rate also increased with increase in mass flow rate

REFERENCES

[1] Padrela, L.; Rodrigues, M.A.; Velaga, S.P.; Matos, H.A.; Azevedo, E.G. (2009)."Formation of indomethacin–saccharin cocrystals using supercritical fluid technology". European Journal of Pharmaceutical Sciences 38(1):9-12.

[2] Malhotra, Ashok and Satyakam R, “Influence of climatic parameters on optimal design of supercritical power plants” IECEC, Energy Conversion Engineering Conference, pp. 1053–1058

[3] Y.T.Ge; L. Li; X.Luo “Performance evaluation of a low-grade power generationsystem with CO2 transcritical power cycles”, Applied energy volume 227, 1 October2018, Pages 220-230.

[4] Hall, W. B. (1971) Heat transfer near the critical points, Advances in HeatTransfer, Vol. 6, Academic Press, New York.

[5] Span, Roland; Wagner, Wolfgang (1996). "A New Equation of State for Carbon Dioxide Covering the Fluid Region from the Triple□Point Temperature to 1100 K at Pressures up to 800 MPa". Journal of Physical and Chemical Reference Data. 25 (6):1509–1596.

[6] https://pubchem.ncbi.nlm.nih.gov/compound/isobutane

[7] Nobuyoshi Tsuzuki;YasuyoshiKato;TakaoIshiduka “High performance printedcircuit heat exchanger” Applied thermal engineering Volume 27, Issue 10, July 2007,Pages 1702-1707.

[8] Yoon, S.-J.; Sabharwall, P.; Kim, E.-S. Numerical study on crossflow printed circuitheat exchanger for advanced small modular reactors. Int. J. Heat Mass Transf. 2014,70, 250–263.

[9] Tsuzuki, N.; Kato, Y.; Ishiduka, T. High Performance Printed Circuit HeatExchanger. Appl. Therm. Eng. 2007, 27, 1702–1707.23.

[10] Kim, I.H.; No, H.C. Thermal hydraulic performance analysis of a printed circuitheat exchanger using a helium–water test loop and numerical simulations. Appl.Therm. Eng. 2011, 31, 4064–4073.

[11] Kim, I.H.; No, H.C.; Lee, J.I.; Jeon, B.G. Thermal hydraulic performance analysisof the printed circuit heat exchanger using a helium test facility and CFD simulations.Nucl.Eng. Des. 2009, 239, 2399–2408.

[12] Kim, I.H.; No, H.C. Physical model development and optimal design of PCHE for intermediate heat exchangers in HTGRs. Nucl. Eng. Des. 2012, 243, 243–250.

[13] Mylavarapu, S.K.; Sun, X.D.; Christensen, R.N.; Unocic, R.R.; Glosup, R.E;Patterson, M.W. Fabrication and design aspects of high-temperature compact diffusionbonded heat exchangers. Nucl.Eng. Des. 2012, 249,49–56.

[14] Mortean, M.V.V.; Paiva, K.V.; Mantelli, M.B.H. Diffusion bonded cross-flow compact heat exchangers: Theoretical predictions and experiments. Int. J. Therm. Sci.2016, 110, 285–298.

[15] Hun, K.I.; Xiaoqin, Z.; Christensen, R.; Sun, X. Design study and cost assessment ofstraight, zigzag, S-shape, and OSF PCHEs for a FLiNaK-SCO2 Secondary HeatExchanger in FHRs. Ann. Nucl. Energy 2016, 94,129-137.

[16] Natesan, K.; Moisseytsev, A.; Majumdar, S. Preliminary issues associated withthe next generation nuclear plant intermediate heat exchanger design. J. Nucl. Mater.2009, 392, 307–315.

[17] Hosseini, S.B.; Khoshkhoo, R.H.; Malabad, S.M.J. Experimental and numericalinvestigation on particle deposition in a compact heat exchanger. Appl. Therm. Eng.2017, 115, 406–417.

[18] Starace, G.; Fiorentino, M.; Longo, M.P.; Carluccio, E. A hybrid method for the cross flow compact heat exchangers design. Appl. Therm. Eng. 2017, 111, 1129–1142.

[19] Park, M.Y.; Song, M.S.; Kim, E.S. Development of tritium permeation model forPrinted Circuit Heat Exchanger. Ann. Nucl. Energy 2016, 98, 166–177.24.

[20] Baek, S.; Kim, J.; Jeong, S.; Jung, J. Development of highly effective cryogenic printed circuit heat exchanger (PCHE) with low axial conduction. Cryogenics 2012,52, 366–374.

[21] Kim, I.H.; No, H.C. Thermal–hydraulic physical models for a printed circuit heatexchanger covering he, he–CO2 mixture, and water fluids using experimental data andcfd. Exp. Therm. Fluid Sci. 2013, 48, 213–221.

[22] Lee, S.-M.; Kim,W.Y. Comparative study on performance of a zigzag printedcircuit heat exchanger with various channel shapes and configurations. Int. J. HeatMass Transf. 2013, 49, 1021–1028.

[23] Lee, S.-M.; Kim, W.Y. Multi-objective optimization of arc-shaped ribs in the channels of a printed circuit heat exchanger. Int. J. Therm. Sci. 2015, 94, 1–8.

[24] MatteoMarchionni; Lei Chai; Giuseppe Bianchi; Savvas A. Tassou “Numerical modelling and transient analysis of a printed circuit heat exchanger used as recuperator for supercritical CO2 heat to power conversion systems” Applied thermal engineering (2019).

[25] Young-JinBaik ;SangwooJeon; Byeongil Kim; DaechanJeon; Chan Byon “Heat transfer performance of wavy-channeled PCHEs and the effects of waviness factors”, IJHMT June 2017.

[26] Amjad Farah; Glenn Harvel; Igor Pioro. "Analysis of computational fluid dynamics code FLUENT capabilities for supercritical water heat transfer application in vertical bare tubes" Journal for nuclear engineering and radiation science (2016).

[27] Muhammad Saeed; Man-Hoe Kim “Thermal-hydraulic analysis of sinusoidal fin based printed circuit heat exchangers for supercritical CO2 Brayton cycle” EnergyConversion and Management, Volume 193, 1 August 2019, Pages 124-139.

[28] Zhongchao Zhao; Kai Zhao; DandanJia; Pengpeng Jiang “Numerical Investigation on the Flow and Heat Transfer Characteristics of Supercritical Liquefied Natural Gasin an Airfoil Fin Printed Circuit Heat Exchanger” Applied thermal engineering Feb201925.

[29] Zhongchao Zhao; Yimeng Zhou; Xiaolong Ma; Xudong Chen; Shilin Li and ShanYang "Numerical Study on Thermal Hydraulic Performance of Supercritical LNG inZigzag-Type Channel PCHEs" Applied Thermal Engineering Feb 2019.

[30] JingzheXie; Hong bin; YanBengt; Sun dén; GongnanXie "A numerical prediction on heat transfer characteristics from a circular tube in supercritical fluid crossflow". Applied Thermal Engineering Volume 153, 5 May 2019, Pages 692-703.

[31] SangwooJeon; Young-JinBaik; Chan Byon; Woojin Kim "Thermal performanceof heterogeneous PCHE for supercritical CO2 energy cycle" IJHMT: July 2016.