Journal of Renewable Energy and Sustainable Development (RESD) Volume 4, Issue 1, June 2018 - ISSN 2356-8569
http://dx.doi.org/10.21622/RESD.2018.04.1.014

A Review of Using Supercritical CO_2 Brayton Cycle in Renewable Energy Applications

Wen-xiao Chu, Katrine Bennett, Jie Cheng and Yi-Tung Chen*
Department of Mechanical Engineering, University of Nevada, Las Vegas, NV 89154, USA
*Corresponding author: Tel: +1 (702)895-1202
*yitung.chen@unlv.edu

***Abstract* -** Supercritical carbon dioxide (sCO_2), which is an environmentally friendly working fluid, has very good thermal physical properties. Many researchers have studied the heat transfer mechanism and the enhanced heat transfer method of the supercritical CO_2 Brayton cycle (sCO_2-BC). The sCO_2-BC has many applications including the next generation of Fast Cooling Reactor (FCR), solar power system, extraction process and heat pump system. The sCO_2-BC provides high efficiency and high compactness, which is important because system miniaturization is vital to these developing technologies. The present paper reviews the recent references on the research progress of the sCO_2-BC system. Furthermore, it discusses the analysis of key components such as the compressor, turbine and heat exchanger, which differ from the devices used in the conventional steam Rankine cycle due to the special thermal properties of sCO_2. Finally, the researchers propose some recommendations towards the development of sCO_2-BC system for future work.

***Keywords* -** Supercritical CO_2 Brayton cycle; Compressor; Turbine; Heat exchanger

I. INTRODUCTION

Carbon emissions are increasing rapidly due to the increasing rate of energy consumption by human beings. The utilizations of renewable energy conversion systems, like nuclear and solar energies, are imperative to slow or stop the environment pollution and destruction caused by carbon emissions. Carbon dioxide (CO_2), which is an environmentally friendly working fluid, has excellent thermal properties when used in a supercritical state. Supercritical CO_2 (sCO_2) is capable of performing expansion working with a lower pressure residence when compared with steam. For this reason, Feher [1] proposed using sCO_2 as a working fluid in the Brayton cycle in 1967. The sCO_2 Brayton cycle (sCO_2-BC) is an attractive working fluid for nuclear reactor systems [2-4], solar power systems [5-7] and other renewable systems [8-11], because of its high overall efficiency due to special thermal properties [12]. The density of sCO_2 is of the same order of magnitude as water. However, the sCO_2 viscosity is similar to that of air. Fig. 1 illustrates the overall cycle efficiency of the sCO_2-BC evaluated from the turbine inlet temperature in the reactor system compared with other thermal cycles [3]. The sCO_2-BC has a much higher efficiency, than other cycles, when the turbine inlet temperature is over 550°C. It is possible for the overall efficiency of the sCO_2-BC to exceed 50%. The cycle efficiency of the sCO_2-BC with the turbine inlet temperature of 550°C is expected to be compared with the helium cycle at 750°C, which means that the cost of materials can significantly be decreased. Thus, the sCO_2-BC has great potential for industrial applications [2].

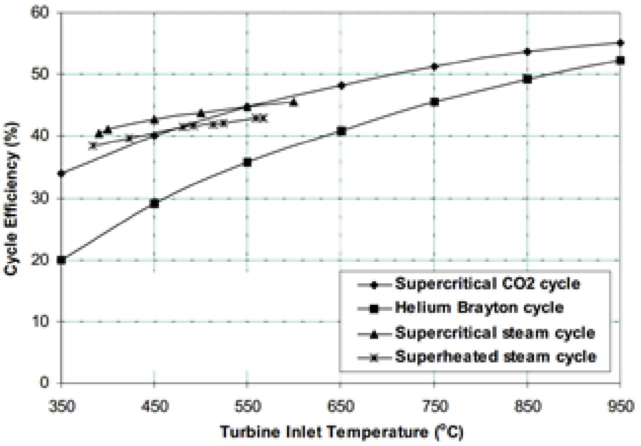

Fig .1. Comparison of power cycle options [3]

Due to the excellent thermal properties of sCO_2, the sCO_2-BC requires significant fewer turbine stages than a cycle using helium or steam under the same thermal power level. Additionally, the operating pressure of sCO_2-BC is always higher than 10 MPa, which allows the compressor, turbine and heat exchanger to be more compact [13]. On the other hand, it is crucial to design and optimize such components for a long-term operation under high temperature and high-pressure conditions. Therefore, the safety, stability and reliability of the operating components in the system should be considered and studied comprehensively [14,15].

In this paper, the performance evaluation, system optimization and economic analysis studies of sCO_2-BC systems from the last five years are reviewed. Other studies of related key components, such as the compressor, turbine and heat exchanger, are introduced briefly. Then, some recommendations are proposed based on the latest studies.

II. STUDIES ON THE SCO_2-BC SYSTEM

The original thermo-dynamic process of sCO_2-BC is shown in Fig. 2, with only some basic components illustrated. In order to improve the overall efficiency of sCO_2-BC, some more complex system compositions are developed. Wang et al. [16] summarize the six typical layouts of sCO_2-BC. These include the simple recuperation cycle, recompression cycle, precompression cycle, intercooling cycle, partial-cooling cycle and split expansion cycle. The derivative relationships between these six typical layouts of sCO_2-BC are shown in Fig. 3. It can be seen that the systems are gradually improved as the necessary components are added into the original cycle to overcome the deficiencies.

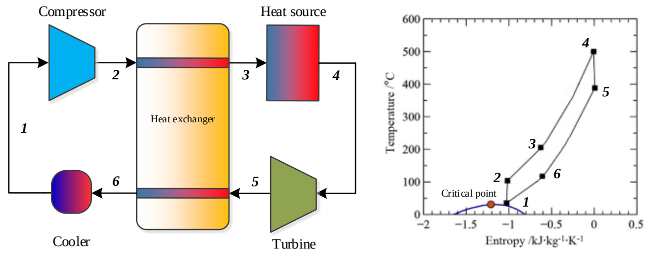

Fig .2. Original supercritical CO_2 Brayton cycle (sCO_2-BC)

The sCO_2-BC can be used in the very high temperature reactor (VHTR) and the fast cooled reactor, which are proposed by the U.S. Department of Energy's Next Generation Nuclear Plant (NGNP) [17]. The simplified design and compact size of the sCO_2-BC may reduce the installation, maintenance and operation cost [7]. Dostal et al. [2-4] created the preliminary design for the compressor, turbine and heat exchanger of the sCO_2-BC in a 600 MW reactor system including detailed volume and the cost estimation. Furthermore, three typical direct cycle designs were further investigated, in which the plant layout and the control scheme design were also included.

With the growing interest in renewable energy, the sCO_2-BC applicability in the field of solar energy is investigated. The sCO_2-BC configurations were explored and optimized for use in a concentrating solar power (CSP) application combined with a dry cooling process, which might achieve the efficiency with 50% or greater [5]. Ortega et al. [6] analyzed the sCO_2-BC in a solar receiver with the power of 0.3-0.5 MW using MATLAB, which can predict the thermal performance of the receiving equipment coupling with the radiation mechanisms. Moreover, it was proposed that the transient nature of the solar resource is the biggest challenge in the CSP system. Nami et al. [14] proposed a standard for evaluating the compressor, turbine, recuperator and cooler considering the factors of energy, economic and environment. Iverson et al. [18] studied the behavior of sCO_2-BC in response to a fluctuating thermal input. The investigation was similar to short-term transient environments and the results showed good agreement with experimental data. Padilla et al. [19] conducted a multi-objective optimization of the compressor, turbine and recuperator on the thermal performance of the sCO_2-BC. It was determined that the more compact characteristics of designing a compressor and turbine operating with the supercritical fluid must be overcome in order to successfully bring the technology to the market. These challenges include the fact that all the components should be designed with a more compact structure because of the miniaturization characteristics of sCO_2-BC. Recent studies focused on optimizing the design of the key components, like the compressor, turbine and heat exchanger, which is described next.

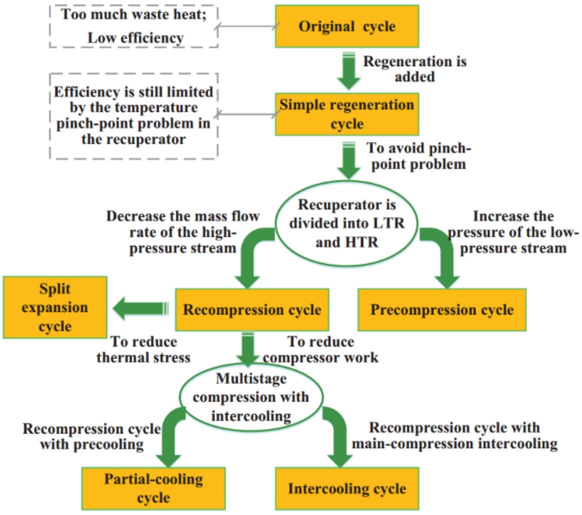

Fig .3. Schematic of derivative relationships of six typical sCO_2-BC [16]

III. STUDIES OF SCO_2-BC COMPONENTS

1. Supercritical CO_2 Compressor and Turbine

The compressor increases the working fluid pressure from a low to a very high pressure, which can be seen in the Temperature-Entropy (T-S) diagram shown in Fig. 2. Cardemil et al. [20] recognized that CO_2 has better comprehensive performance when operated at supercritical conditions. The effect of the compressor on the overall efficiency of the sCO_2-BC was studied by Dyreby [21]. The results indicated that the overall efficiency could be improved by increasing the compressor inlet pressure. However, it was found that the increase of compressor outlet pressure never affects the thermal efficiency. Ibsaine [22] presented a new compressor design concept, which was especially suited for sCO_2 heat pump applications. The compressor consists of an integrated thermal system that consists of a thermal compressor and a conventional vapor compression heat pump. The computational model was verified by comparison with experimental measurements from the thermal compressor prototype. In Ibsaine’s study, the impacts of the size of dead spaces and leaks between the displacer and the cylinder wall were studied parametrically. Pecnik [23] investigated a high-speed centrifugal compressor operating with sCO_2 and compared the results with data from tests in the Sandia sCO_2 compression loop facility. Then, Lettieri et al. [24] studied a multistage compressor operating with supercritical CO_2 by CFD method. The thermal properties of supercritical CO_2 was calculated with the National Institute of Standards and Technology real gas model [25]. In order to improve the stage efficiency, a vaned diffuser was analyzed instead of the standard vaneless diffuser in order to decrease the meridional velocity and widen the gas path. Rinaldi el al. [26] calculated the compressor map for three different rotational speeds (45 krpm, 50 krpm and 55 krpm) and the methodology and results were validated against experimental data from the Sandia National Laboratory. The comprehensive assessment of sCO_2 real gas effects is important for evaluating the performance of compressor considering the high variability of thermal properties of sCO_2. Baltadjiev [27] investigated the centrifugal compressors at different thermodynamic conditions relative to the pseudo-critical point of CO_2. The results indicated that it has a reduction of 9% in the choke margin of the stage due to the thermal properties variations and the condensation was not a concern at the investigated operating conditions.

The turbine is the component used for power generation, and as such, it can directly indicate the system efficiency. The sCO_2 turbine is far smaller than the steam turbine due to its low pressure-ratio. Furthermore, the sCO_2 turbine is much simpler than the steam one because it does not need to allow for phase change and moisture separation. Kato et al. [28] found that the sCO_2 gas turbine reactor system, with a partial pre-cooling cycle, attained the excellent cycle efficiency of 45.8% at the temperature of 650ºC. Chen [29] proposed the centrifugal prototype turbine using the sCO_2-BC and analyzed the performance with experimental and numerical methods. The shape and size of the nozzle of the supercritical CO_2 turbine was optimized and it was found that choked flow did not occur when the diameter of the nozzle was larger than 0.7 mm. Additionally; the turbine output torques and the electric power generation can be improved with the increase of the nozzle inner diameter. The achievable thermal cycle efficiencies of the steam turbine cycle, helium turbine cycle and sCO_2 turbine cycle were studied and compared by Ishiyama [30]. These efficiencies were found to be 40%, 34% and 42%, respectively, when the heat source temperature is 480ºC. Furthermore, the volume of a sCO_2 turbine was estimated to be only half that of a steam turbine generating the same power.

2. Supercritical CO_2 Heat Exchanger

In the sCO_2-BC, the recuperator and cooler, which play important roles in maintaining safe operations, always have significant impacts on the efficiency of the whole system. The shell-and-tube heat exchanger (STHE), which has been used for nearly a hundred years and has a mature manufacturing process, is now in wide use in the high pressure and high temperature systems [31]. However, the application of the STHE is limited by its required large volume and high cost when systems require compactness and miniaturization. In recent decades, the HEATRIC Company has developed a new type of printed circuit heat exchanger (PCHE) [32]. This new PCHE meets compactness requirements and can reliably operate for long term in extreme temperature and pressure conditions. The PCHE has performed excellently when used in the SCO_2-BC system.

Mylavarapu et al. [33-36] at Ohio State University investigated the PCHE in the high temperature helium facility (HTHF) with experimental and numerical methods. The straight fins of Alloy 617 plates were fabricated by photochemical etching and assembled by diffusion bonding. The experimental test data could be used to determine the design operating conditions for the PCHE in the HTHF. Ma et al. [37] also analyzed the thermal and hydraulic performance of a PCHE with zigzag fins. It was found that the flow could not be fully-developed at the high temperature due to the significant variation of the thermal physical properties of sCO_2. Tsuzuki et al. [38-40] developed a new PCHE with S-shaped fins. They validated numerically that the PCHE with S-shape fins had the same heat transfer performance as the zigzag PCHE but with the benefit of one-fifth of the pressure drop. With continued focus on fin structures, the heat transfer performance of a PCHE with airfoil shaped fins was proposed and analyzed by Kim et al. [41]. It can be seen that the PCHE with airfoil shaped fin can obtain the same heat transfer performance as the zigzag channel PCHE with only 1/12 the pressure drop. This is due to the streamlined fin shape and the increase of heat transfer area. Furthermore, Xu et al. [42] analyzed the airfoil fin structure parametrically and proposed that it was necessary to reduce the flow resistance along the flow direction in order to improve the comprehensive thermal hydraulic performance of the PCHE.

IV. CONCLUSIONS

The sCO_2-BC is an efficient thermodynamic cycle due to the excellent thermal properties of the sCO_2, which have significantly improved the systems overall performance when compared with other conventional cycles. Researchers have studied the sCO_2-BC system extensively, including performance evaluation and component optimization.

- The sCO_2-BC has very high overall efficiency, possibly above 50%. The sCO_2-BC may be used in the next generation reactor systems and solar power systems, which can significantly reduce the system volume.
- It is a challenge to design the compressor and turbine with sCO_2 working fluid for stable system operation. The sCO_2 compressor and turbine are far smaller than conventional ones due to the low pressure ratio, which can definitely contribute to the system miniaturization.
- The PCHE is a compact heat exchanger with a volume of 85% that of a comparable STHE. Complex fin structures for the PCHE have been developed; ranging from continuous zigzag shape to discontinuous airfoil shape, which aim to improve the comprehensive performance.

According to the investigation review above, some recommendations for future work of the sCO_2-BC system are proposed. Firstly, the material problem is now becoming the focus, due to system operating temperatures and pressures exceeding 700°C and 20 MPa, respectively. Secondly, the behavior and the performance of the compressor and turbine operating close to the critical point, should be tested and evaluated due to the high variability of sCO_2 thermal properties. Finally, the dynamic analysis of the entire system should be studied with transient analysis in cases of great fluctuation, to ensure the system should operate near the stability point very well.

V. ACKNOWLEDGEMENTS

This material is based upon work financially supported by the U.S. National Science Foundation under Grant No. IIA-1301726.

REFERENCES

[1] E.G. Feher. "The supercritical thermodynamic power cycle," Energy conversion, vol. 8, no. 2, pp 85-90, 1968.

[2] V. Dostal, M.J. Driscoll and P. Hejzlar et al. "A supercritical CO2 gas turbine power cycle for next-generation nuclear reactors," American Society of Mechanical Engineers, pp. 567-574, 2002.

[3] V. Dostal, M.J. Driscoll and P. Hejzlar et al. "A supercritical CO2 cycle for fast gas-cooled reactors," American Society of Mechanical Engineers, pp. 683-692, 2004.

[4] V. Dostal. "A supercritical carbon dioxide cycle for next generation nuclear reactors," Massachusetts Institute of Technology, 2004.

[5] M.A. Reyes-Belmonte, A. Sebastian and M. Romero et al. "Optimization of a recompression supercritical carbon dioxide cycle for an innovative central receiver solar power plant," Energy, vol. 112, pp. 17-27, 2016.

[6] J. Ortega, S. Khivsara and J. Christian et al. "Coupled modeling of a directly heated tubular solar receiver for supercritical carbon dioxide Brayton cycle: Optical and thermal-fluid evaluation," Applied Thermal Engineering, vol. 109, pp. 970-978, 2016.

[7] C.S. Turchi, Z.W. Ma and T. W. Neises et al. "Thermodynamic study of advanced supercritical carbon dioxide power cycles for concentrating solar power systems," ASME Journal of Solar Energy Engineering-Transactions, vol. 135, no. 4, pp. 7, 2013.

[8] M. Chauvet, M. Sauceau and J. Fages. "Extrusion assisted by supercritical CO2: A review on its application to biopolymers," Journal of Supercritical Fluids, vol. 120, pp. 408-420, 2017.

[9] S.M.S. Mahmoudi, A.D. Akbari and M.A. Rosen. "Thermoeconomic analysis and optimization of a new combined supercritical carbon dioxide recompression Brayton/Kalina cycle," Sustainability, vol. 8 , no. 10, pp. 19, 2016.

[10] M. Mecheri and Y. Le Moullec. "Supercritical CO2 Brayton cycles for coal-fired power plants," Energy, vol. 103, pp. 758-771, 2016.

[11] M. Mehrpooya, P. Bahramian and F. Pourfayaz et al. "Introducing and analysis of a hybrid molten carbonate fuel cell-supercritical carbon dioxide Brayton cycle system," Sustainable Energy Technologies and Assessments, vol. 18, pp. 100-106, 2016.

[12] P. Kumar and K. Srinivasan. "Carbon dioxide based power generation in renewable energy systems," Applied Thermal Engineering, vol. 109, pp. 831-840, 2016.

[13] T. Ma, W.X. Chu and X.Y. Xu et al. "An experimental study on heat transfer between supercritical carbon dioxide and water near the pseudo-critical temperature in a double pipe heat exchanger," International Journal of Heat and Mass Transfer, vol. 93, pp. 379-387, 2016.

[14] H. Nami, S.M.S. Mahmoudi and A. Nemati A. "Exergy, economic and environmental impact assessment and optimization of a novel cogeneration system including a gas turbine, a supercritical CO2 and an organic Rankine cycle," Applied Thermal Engineering, vol. 110, pp. 1315-1330, 2017.

[15] H. Zhao, Q.H. Deng and W.T. Huang et al. "Thermodynamic and economic analysis and multi-objective optimization of supercritical CO2 Brayton cycles," ASME Journal of Engineering for Gas Turbines and Power-Transactions, vol. 138, no.8, pp. 9, 2016.

[16] K. Wang, Y.L. He and H.H. Zhu. Integration between supercritical CO2 Brayton cycles and molten salt solar power towers: A review and a comprehensive comparison of different cycle layouts," Applied Energy, vol. 195, pp. 819-836, 2017.

[17] R. Mizia, D. Clark and M. Glazoff et al. Progress Report for Diffusion Welding of the NGNP Process Application Heat Exchangers, December, 2011.

[18] B.D. Iverson, T.M. Conboy and Pasch et al. "Supercritical CO2 Brayton cycles for solar-

thermal energy," Applied Energy, vol. 111, pp. 957-970, 2013.

[19] R.V. Padilla, RV Y.C.S.Too YCS and R. Benito R et al. "Thermodynamic feasibility of alternative supercritical CO2 Brayton cycles integrated with an ejector," Applied Energy, vol. 169, pp. 49-62, 2016.

[20] J.M. Cardemil and A.K. da Silva. "Parametrized overview of CO2 power cycles for different operation conditions and configurations - An absolute and relative performance analysis," Applied Thermal Engineering, vol. 100, pp. 146-154, 2016.

[21] J. Dyreby, S. Klein S and G. Nellis G et al. "Design considerations for supercritical carbon dioxide Brayton cycles with recompression," ASME Journal of Engineering for Gas Turbines and Power-Transactions, vol. 136, no. 10, pp. 9, 2014.

[22] R. Ibsaine, J.M. Joffroy and P. Stouffs. "Modelling of a new thermal compressor for supercritical CO2 heat pump," Energy, vol. 117, pp. 530-539, 2016.

[23] R. Pecnik, E. Rinaldi and P. Colonna. "Computational fluid dynamics of a radial compressor operating with supercritical CO2. ASME Journal of Engineering for Gas Turbines and Power-Transactions, vol. 134, no. 12, pp. 8, 2012.

[24] C. Lettieri, N. Baltadjiev and M. Casey M et al. "Low-flow-coefficient centrifugal compressor design for supercritical CO2. ASME Journal of Turbomachinery-Transactions, vol. 136, no. 8, pp. 9, 2014.

[25] NIST Web-Page, From. Available: http://webbook.nist.gov/chemistry/fluid, July 31, 2009.

[26] E. Rinaldi, R. Pecnik and P. Colonna. "Computational fluid dynamic simulation of a supercritical CO2 compressor performance map," ASME Journal of Engineering for Gas Turbines and Power-Transactions, vol. 137, no. 7, pp. 7, 2015.

[27] N.D. Baltadjiev, C. Lettieri and Z.S. Spakovszky . An investigation of real gas effects in supercritical CO2 centrifugal compressors," ASME Journal of Turbomachinery-Transactions, vol. 137, no. 9, pp. 13, 2015.

[28] Y. Kato, T. Nitawaki and Y. Muto. "Medium temperature carbon dioxide gas turbine reactor," Nuclear Engineering and Design, vol. 230, no.1-3, pp. 195-207, 2004.

[29] M.F. Chen, H. Yamaguchi and X.W. Zhang et al. "Performance analyses of a particularly designed turbine for a supercritical CO2-based solar Rankine cycle system. International Journal of Energy Research," vol. 39, no. 13, pp. 1819-1827, 2015.

[30] S. Ishiyama, Y. Muto and Y. Kato et al. "Study of steam, helium and supercritical CO2 turbine power generations in prototype fusion power reactor," Progress in Nuclear Energy, vol. 50, no. 2-6, pp. 325-332, 2008.

[31] Z.H. Li, Y.L. Zhai and K,Z. Li et al. "A quantitative study on the interaction between curvature and buoyancy effects in helically coiled heat exchangers of supercritical CO2 Rankine cycles," Energy, vol. 116, pp. 661-676, 2016.

[32] Heatric. Compact diffusion-bonded heat exchangers-The future of heat transfer engineering. Heatric Division of Meggitt (UK) Limited: Dorset, UK, 2011.

[33] S. Mylavarapu, X. Sun and J. Figley et al. "Investigation of high-temperature printed circuit heat exchangers for very high temperature reactors," Journal of Engineering for Gas Turbines and Power, vol. 131, no. 6, pp. 062905-7, 2009.

[34] S.K. Mylavarapu, X. Sun and R.N. Christensen et al. "Fabrication and design aspects of high-temperature compact diffusion bonded heat exchangers," Nuclear Engineering and Design, vol. 249, pp. 49-56, 2012.

[35] S.K. Mylavarapu, X.D. Sun and R.E. Glosup et al. "Thermal hydraulic performance testing of

printed circuit heat exchangers in a high-temperature helium test facility," Applied Thermal Engineering, vol. 65, no. 1-2, pp. 605-614, 2014.

[36] S.K. Mylavarapu, X.D. Sun and R.N. Christensen. "Photofabrication and surface roughness of flow channels for a compact high-temperature heat exchanger," Transactions of the American Nuclear Society, vol. 99, pp. 837-839, 2008.

[37] T. Ma, L. Li and X.Y. Xu et al. "Study on local thermal-hydraulic performance and optimization of zigzag-type printed circuit heat exchanger at high temperature," Energy Conversion and Management, vol. 104, pp. 55-66, 2015.

[38] T.L. Ngo, Y. Kato and K. Nikitin et al. "New printed circuit heat exchanger with S-shaped fins for hot water supplier," Experimental Thermal and Fluid Science, vol. 30, no. 8, pp. 811-819, 2006.

[39] N. Tsuzuki, Y. Kato and T. Ishiduka . "High performance printed circuit heat exchanger," Applied Thermal Engineering, vol. 27, no. 10, pp. 1702-1707, 2007.

[40] N. Tsuzuki, M. Utamura and T.L. Ngo . "Nusselt number correlations for a microchannel heat exchanger hot water supplier with S-shaped fins," Applied Thermal Engineering, vol. 29, no. 16, pp. 3299-3308, 2009.

[41] D.E. Kim, M.H. Kim and J.E. Cha JE et al. "Numerical investigation on thermal–hydraulic performance of new printed circuit heat exchanger model," Nuclear Engineering and Design, vol. 238, no. 12, pp. 3269-3276, 2008.

[42] X. Xu, T. Ma and L. Li et al. "Optimization of fin arrangement and channel configuration in an airfoil fin PCHE for supercritical CO2 cycle," Applied Thermal Engineering, vol. 70, no. 1, pp. 867-875, 2014.