© 2018 IJSRST | Volume 4 | Issue 2 | Print ISSN: 2395-6011 | Online ISSN: 2395-602X
Themed Section: Science and Technology

# Heat Transfer Analysis of CANDU 6 Nuclear Reactor using Supercritical Carbon-Dioxide Considering Brayton Cycle

**Lakshmana Kishore T*[1], Dr. Kiran Chaudhari[2], Dr. G. Ranga Janardhana[3]**

*[1]Assistant Professor, Mechanical Engineering, JNTUK University College of Engineering, Vizianagaram, Andhra Pradesh, India

[2]Professor, Mechanical Engineering, MCT's Rajiv Gandhi Insitute of Technology, Mumbai, Maharashtra, India

[3]Professor, Mechanical Engineering, JNTUA University college of Engineering, Anantapuramu, Andhra Pradesh, India

## ABSTRACT

Currently available CANDU 6 nuclear reactor uses heavy water as working fluid and contains two circuits – Primary and Secondary Circuits, one for heat input and the other for the power generation. In order to increase the heat transfer and for better performance, supercritical fluids (SCF's) are selected as the working fluid. Using supercritical fluids instead of two circuits, one circuit is sufficient for both heat input and power generation. Supercritical carbondioxide is used as the working fluid and Brayton cycle is considered for the design and analysis of the circuit. The pressure drop and the various factors affecting the heat transfer are analysed. Optimization of Pressure is carried out for the circuit. The circuit end states, thermal efficiency and number of pressure tubes are finalized for simple, Regenerative, Regeneration with intercooling and Regeneration split Brayton cycle.

**Keywords:** Nuclear Reactor, Pressure Tube, Supercritical Fluids, Brayton Cycle

## I. INTRODUCTION

Presently, the CANDU 6 Nuclear Reactor is using Heavy water as the working fluid. In this paper, the circuit design and analysis of the Nuclear Reactor is done using Supercritical Carbon-dioxide as the working fluid.

CANDU6 nuclear reactor consists of two circuits: 1. Primary circuit and 2. Secondary circuit. The primary circuit is used for Heat generation and secondary circuit is for power generation. By using supercritical fluids in CANDU6 nuclear reactor, both heat generation and power generation is done in a single circuit. By considering Brayton cycle, the single circuit consists of i) Pressure tube for heat generation; ii) Turbine for power generation; iii) Heat exchanger for heat dissipation and iv) compressor to complete the Brayton cycle. Furthur more, Regenerator, Intercooler and compressors are used for the improvement of the cycle.

## II. MODELLING AND VALIDATION OF THE PRESSURE TUBE

From [3] the dimensions of the pressure tube of the CANDU 6 Nuclear Reactor is modelled using CATIA V5.The pressure tube contains 12 fuel bundles and each fuel bundle contains 37 fuel rods. The modeled fuel bundle is shown in the figure 1.

**Figure 1.** Modelled Fuel bundle in CATIA-V5

There are total of 380 such pressure tubes forming the core of a nuclear reactor using heavy water, through

IJSRST184193 | Received : 10 Jan 2018 | Accepted : 22 Jan 2018 | January-February-2018 [ (4) 2: 355-360]

which heat addition takes place. The modeled pressure tube is imported to ANSYS-CFX for the analysis using different fluids. The Validation of the pressure tube model is done in [1].

## III. SUPERCRITICAL FLUID

Supercritical fluid is any substance at a pressure and temperature above its critical point, where distinct liquid and gas phases do not exist. Supercritical fluids combine useful properties of gas and liquid phases. Their behaviour is near gas from some aspects and near liquid in terms of different features. A supercritical fluid provides a gas like characteristic when it fills a container and it takes the shape of container. The motion of molecules are quite similar to gas molecules. On the other hand, a supercritical fluid behaves like a liquid because its density property is near liquid and, thus supercritical fluid shows a similarity to liquid in terms of dissolving effect. The formation of a supercritical fluid is the result of dynamic equilibrium. In this paper, circuit design is performed by using supercritical carbondioxide.

The properties of supercritical carbondioxide taken are as shown in the following table:

**Table 1.**Properties of Supercritical Carbon-dioxide

| Property | Value |
|---|---|
| Molar Mass (g/mol) | 44.01 |
| Critical Temperature (K) | 305.15 |
| Critical Pressure (MPa) | 7.4 |
| Critical Volume ($cm^3$/mol) | 94 |
| Acentric Factor | 0.22394 |
| Boiling Point (K) | 194.75 |

## IV. DESIGN AND ANALYSIS OF REACTOR CIRCUIT

The reactor circuit design and analysis is performed considering Brayton cycle. As specified, the components of the circuit for simple Brayton cycle will be Pressure tube, Turbine, Heat Exchanger and a Compressor. The turbine and the compressor processes are considered to be isentropic, heat rejection in the heat exchanger is isobaric and pressure drop in the pressure tube is considered. The simple Brayton cycle circuit is shown in the figure 2.

As the critical pressure and temperature of carbondioxide are 7.4 MPa and 305.15K, the supercritical fluid operating values will be above critical pressures.

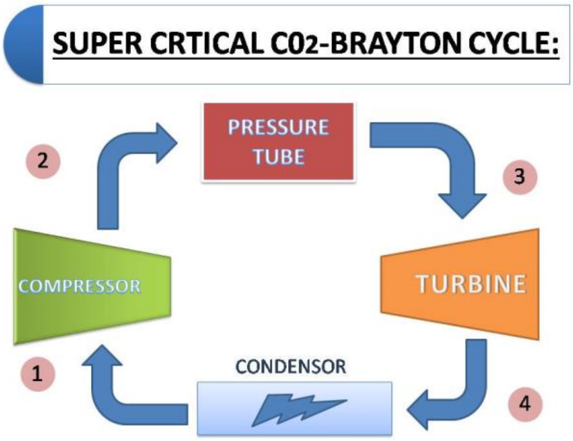

**Figure 2.** Block diagram of simple Brayton cycle

As in all the advanced turbines, maximum working temperature is at $550^0$C, the temperature at the inlet of the turbine is fixed at $550^0$C. Now, the pressure at the entrance of the turbine is to be optimized.

### A. Optimization Of Pressure At The Entrance Of The Turbine:

Different analysis are being performed on the pressure tube at different operating pressures at the entrance of the turbine and a graph (figure 3) is drawn between percentage increase in net work output per MPa pressure and output pressure.

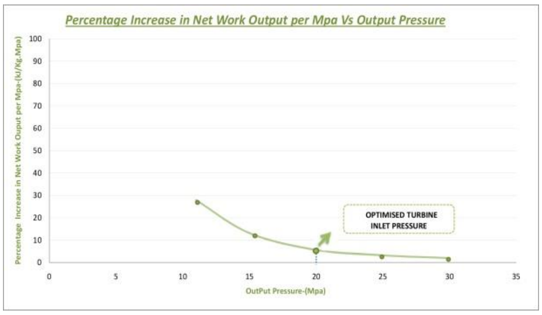

**Figure 3.** Graph between Percentage increase in Net work ooptput per MPa Vs Output Pressure.

Form the above graph, it is seen that the Percentage increase in net work output per MPa is less than 5% when the pressure is increased from 20 Mpa to 21 MPa. So, the optimized pressure taken is 20Mpa for supercritical carbondioxide. Different Brayton cycles have been designed with this optimized pressure and temperature which are elaborated as follows:

i) **Simple Brayton cycle:** The block diagram of the Simple Brayton cycle is shown in the figure 2. For the optimized pressure and temperature, the cycle end state values are determined and those are shown in the Temperature-Entropy graph (figure 4).

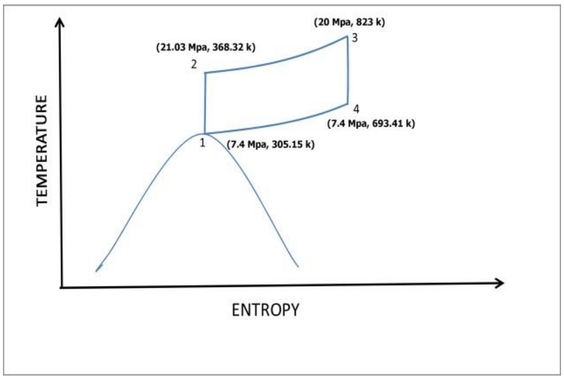

**Figure 4.** Temperature-Entropy diagram for a simple Brayton cycle at optimized pressure

ii) **Regenerative Brayton cycle:** The block diagram of the Regenerative Brayton cycle is shown in the figure 5.

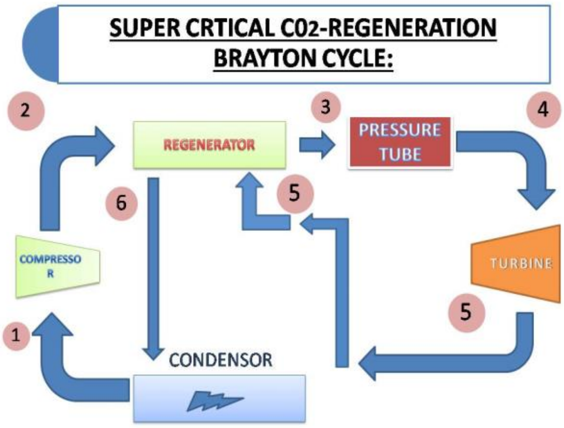

**Figure 5.** Block diagram of Regenerative Brayton cycle

Considering the effectiveness of the Regenerator to be 100%, for the optimized pressure and temperature, the cycle end state values are determined and those are shown in the Temperature-Entropy graph (figure 6).

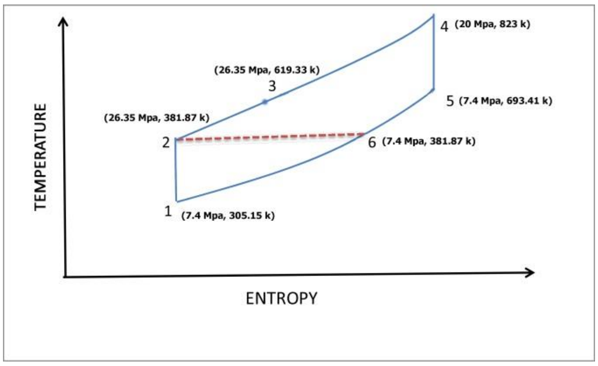

**Figure 6.** Temperature-Entropy diagram for a Regenerative Brayton cycle at optimized pressure

iii) **Regenerative Brayton cycle with Intercooling:** The block diagram of the Regenerative Brayton cycle with intercooling is shown in the figure 7.

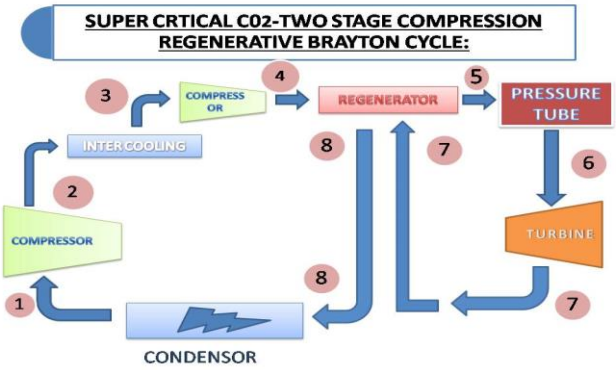

**Figure 7.** Block diagram of regenerative Brayton cycle with Intercooler

For the optimized pressure and temperature, the cycle end state values are determined and those are shown in the Temperature-Entropy graph (figure 8).

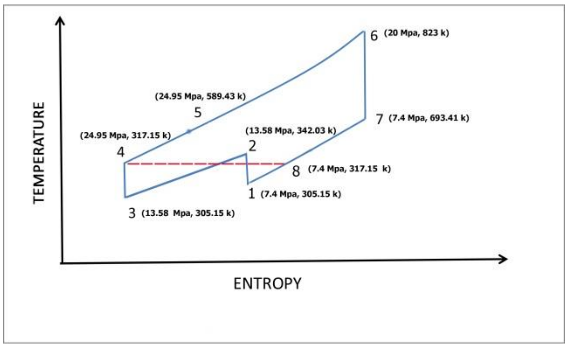

**Figure 8.** Temperature-Entropy diagram for regenerative Brayton cycle with Intercooler at optimized pressure

**iv) Regenerative Brayton split flow cycle:**

The block diagram of the Regenerative Brayton split flow cycle is shown in the figure 9.

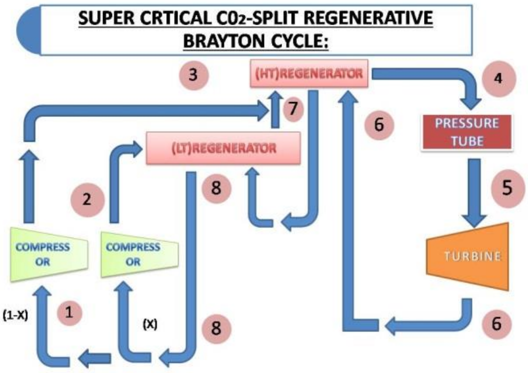

**Figure 9.** Block diagram of Split-Regenerative Brayton cycle

For the optimized pressure and temperature, the cycle end state values are determined and those are shown in the Temperature-Entropy graph (figure 10).

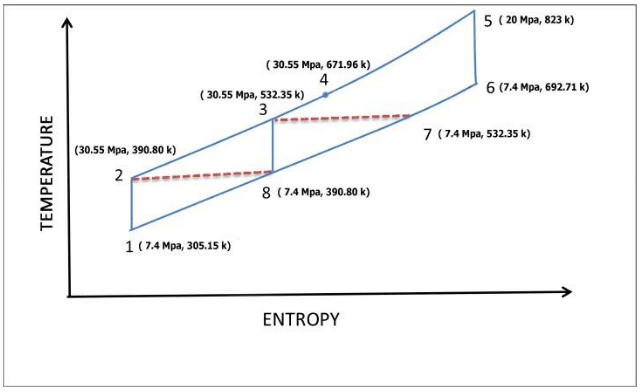

**Figure 10.** Temperature-Entropy diagram for a Split-Regenerative Brayton cycle at optimized pressure

## V. RESULTS AND DISCUSSIONS

With reference to the above different cycles analysed, the net work output, mass flow rate and the number of pressure tubes required are determined. The calculated values are incorporated in the Table:2.

**Table 2.** Calculated parameters of different cycles

| S.NO. | Cycle | Net Work (kJ/kg) | Mass flow rate (kg/s) | No. of Pressure tubes |
|---|---|---|---|---|
| 1 | Simple | 113.02 | 15.36 | 346 |
| 2 | Regenerative | 102.39 | 36.27 | 163 |
| 3 | Regeneration with intercooling | 113.77 | 32.83 | 160 |
| 4 | Split Flow | 78.07 | 48.6 | 158 |

For the split cycle, for the optimized pressure and temperature at the entrance of the turbine, 30% of the working fluid is being split before the completion of heat rejection process and getting compressed and remaining 70% of the working fluid is completing the cycle. Both these working fluids gets mixed up before the high temperature regeneration process.

## VI. CONCLUSION

For supercritical carbon dioxide, the pressure and temperature have been optimised at the turbine entrance. The different options of the Brayton cycle for the pressure tube circuit has been studied and analysed using ANSYS-CFX using supercritical carbondioxide. With reference to the Table 2, of the different cycles studied, the regenerative split flow cycle will have less number of operating pressure tubes when compared to the other cycles, but the pressure to be maintained is higher at the entrance of the pressure tube. As the pressure drop is higher in the pressure tube in case of regenerative split flow case, the mass flow rate is higher. The maximum efficiency occurs in the Split flow Regenerative Brayton cycle.

## VII. REFERENCES

[1]. Lakshmana Kishore.T , Dr. Kiran Chaudhari , Dr. G. Ranga Janardhana, "Computational Characterization of Fluid Flow and Heat Transfer in the Pressure Tube of CANDU 6 Nuclear Reactor with Supercritical CO2," International Journal of Engineering and Technology,Volume 9 Issue 3 June-July 2017, pg.2225-2235.

[2]. Lakshmana Kishore.T , Dr. Kiran Chaudhari , Dr. G. Ranga Janardhana, "Heat Transfer And Fluid Flow Analysis Of Pressure Tube In Candu 6 Nuclear Reactor Using Supercritical Water," SSRG International Journal of Mechanical Engineering (SSRG-IJME) – Special Issue May - 2017, pg.153-158.

[3]. Wm. J. Garland, "A text book on the CANDU Nuclear Power Plant Technology", The Essential CANDU, ISBN 0-9730040.

[4]. Dr. Robin Chaplin, "Genealogy of CANDU Reactors," The Essential CANDU, Chapter 2, ISBN 0-9730040, Dec., 2016.

[5]. Chun K. Chow, and Hussam F. Khartabil, "CONCEPTUAL FUEL CHANNEL DESIGNS FOR CANDU-SCWR,"Nuclear Engineering and Technology, vol.40, Special issue on the 3rd International Symposium on SCWR, Nov. 15, 1999.

[6]. NASA Polynomial format for CHEMKIN-II, GRI-Mech Version 3.0 Thermodynamics released 7/30/99.

[7]. http://webbook.nist.gov/, 2016.

[8]. Alexandru CATANA, Ilie PRISECARU, Daniel DUPLEAC, and Danila NICOLAE, "COMPUTATIONAL FLIUD DYNAMIC APPROACH FOR CANDU6 AND ACR1000 FUEL CHANNEL COOLANT FLOW," ISSN 1454-2358, U.P.B. Sci. Bull., Series D, Vol. 72, Iss. 1, 2010.

[9]. K. Podila, Y.F. Rao, "CFD analysis of flow and heat transfer in Canadian supercritical water reactor bundle," ELSEVIER, 2014.

[10]. Chun K. Chow, and Hussam F. Khartabil, "CONCEPTUAL FUEL CHANNEL DESIGNS FOR CANDU-SCWR," Nuclear Engineering and Technology, vol.40, Special issue on the 3rd International Symposium on SCWR, Nov. 15, 1999.

[11]. R.B. Duffey, I.L. Pioro, B.A. Gabaraev and Yu. N. Kuznetsov, "SCW Pressure-Channel Nuclear Reactors: Some Design Features", the 14th International Conf. on Nuclear Engineering (ICONE-14), Paper 89609, 2006.

[12]. T. Schulenberg, L.K.H. Leung, D. Barady, Y. Oka and K. Yamada, "Supercritical Water-cooled Reactor (SCWR) Development through GIF Collaboration", IAEA-CN-164-5S06.

[13]. Metin Yetisir, Michel Gaudet, Jeremy Pencer, Michael McDonald, David Rhodes, Holly Hamilton, and Laurence Leung, "CANADIAN SUPERCRITICAL WATER-COOLED REACTOR CORE CONCEPT AND SAFETY FEATURES", Canadian Nuclear Laboratories, Stn 42, Chalk River, ON K0j 1P0, Canada.

[14]. D.F. Wang and S. Wang, "A PRELIMINARY CATHENA THERMALHYDRAULIC MODEL OF THE CANADIAN SCWR FOR SAFETY ANALYSIS", Atomic Energy of Canada Limited, Chalk River, ON K0J 1J0, Canada.

[15]. Ajoy Debbarma, K.M Pandey, Procedia Engineering 64 (2013) 507 – 517 "Numerical Analysis of Flow and Heat transfer in Sub-channel of Supercritical Water Reactor".

[16]. Guoli Tang, Hang Shi, Yuxin Wu, Junfu Lu, Zhouhang Li, Qing Liu, Hai Zhang, International Journal of Heat and Mass Transfer 102 (2016) 1082–1092 "A variable turbulent Prandtl number model for simulating supercritical pressure CO2 heat transfer".

[17]. Yoon Y. Bae, International Journal of Heat and Mass Transfer 92 (2016) 792–806 "A new formulation of variable turbulent Prandtl number for heat transfer to supercritical fluids".

[18]. K. Dobashi, A. Kimura, Y. Oka and S. Koshizuka, Nuclear Engineering laboratory, The University of Tokyo, Ibraki 319-11,Japan "Conceptual Design of High Temperature Power Reactor Cooled and Moderated by Supercritical Light Water".

[19]. Lina Zhang, Minshan Liu, Qiwu Dong, Songwei Zhao, Energy and Power Engineering, 2011, 3, 167-173 "Numerical Research of Heat Transfer of Supercritical CO2 in Channels".

[20]. Hongzhi Li, Yifan Zhang, Lixin Zhang, Mingyu Yao, Alan Kruizenga, Mark Anderson, International Journal of Heat and Mass Transfer 98 (2016) 204–218 "PDF-based modeling on the turbulent convection heat transfer of supercritical CO2 in the printed circuit heat exchangers for the supercritical CO2 Brayton cycle".

[21]. Mohammad Mizanur Rahman , Ji Dongxu , Mehrdad Shahmohammadi Beni , Ho Choi Hei , Weidong He , Jiyun Zhao, Annals of Nuclear Energy 97 (2016) 53–65 "Supercritical water heat transfer for nuclear reactor applications".

[22]. Dimmick, G.R., Spinks, N.J., Duffey, R., 1998. "An advanced CANDU reactor with supercritical water coolant: conceptual design features", Proceedings of the Sixth International Conference on Nuclear Engineering (ICONE-6), San Diego, California, USA, May 10–15, Paper-6501.

[23]. I.L. Pioro, H.F. Khartabil, and R.B. Duffey, "Heat Transfer to Supercritical Fluids Flowing in Channels – Empirical Correlations (Survey)", Nuclear Engineering and Design, Vol. 230, No. 1–3, pp. 69–91, 2004.