Computational Characterization of Fluid Flow and Heat Transfer in the Pressure Tube of CANDU 6 Nuclear Reactor with Supercritical CO_2

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***Abstract*— The heat transfer and fluid flow analysis of the pressure tube in the primary circuit of CANDU 6 nuclear reactor is performed by using Supercritical fluids (SCF's) as working fluid. Currently available CANDU 6 nuclear reactor uses heavy water as the working fluid in the primary circuit. In order to increase the heat transfer and for better performance, supercritical fluids (SCF's) are selected as the working fluid. The supercritical fluid used is carbon-dioxide (CO_2). Heavy water is used as the moderator. The pressure tube of the reactor is modelled and analysis is performed using ANSYS-CFX. The solution of the problem is validated using heavy water as working fluid. The pressure drop, velocity variations and the various factors affecting the heat transfer are analysed for the supercritical fluid selected and comparison is made between them.**

Keyword - CANDU 6, Super Critical Fluids (SCF's), Pressure Tube, Nuclear Reactor.

I. INTRODUCTION

The CANDU 6 Nuclear Reactor is using Heavy Water as the working fluid. In this paper the pressure tube of the Nuclear Reactor is studied using Supercritical Carbon-dioxide as the working fluid. The dimensions of the pressure tube taken, are same as that of the CANDU 6 Nuclear Reactor.

A. *CANDU 6 Nuclear Reactor Pressure Tube*

CANDU 6 is the Generation III, 600 MW class heavy-water moderated and cooled pressure tube reactor. Heavy water (D_2O) is a natural form of water that is used as a moderator to slow down the neutrons in the reactor, enabling the use of natural uranium as fuel. Same D_2O is used as the working liquid, responsible for transportation of heat. The dimensions used in the analysis is taken from [1] and [2].

Concept of nuclear reactors with water at supercritical pressures were studied as early as the 1950s and 1960s in the USA and Russia. Similar to the CANDU design, the CANDU-SCWR is moderated with Heavy water. The coolant used is light water at 25 Mpa pressure and with an inlet temperature of 350°C. With SCF's as a coolant the efficiency increased to over 40% [9].

B. *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 fluids 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.

When a material is heated until its specific critical temperature in a closed system, which means at constant pressure, a dynamic equilibrium is generated. This equilibrium includes the same number of molecules coming out of liquid phase to gas phase by gaining energy and going into liquid phase from gas phase by losing energy.

At this particular point, the phase curve between liquid and gas phases disappear and supercritical material appears.

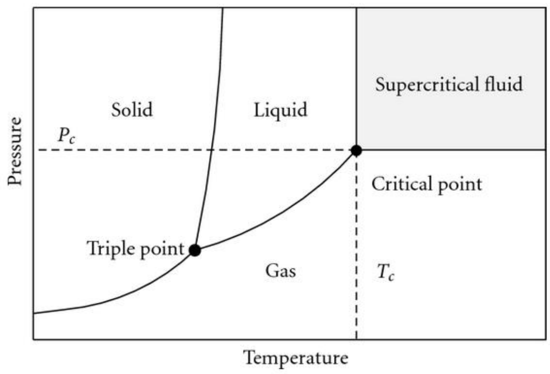

Fig 1: Pressure Vs Temperature for a supercritical fluid

In the phase diagram, the field above critical temperature and critical pressure values is defined as supercritical region. The characteristic properties of a supercritical fluid are density, diffusivity and viscosity. Supercritical values for these features take place between liquids and gases

II. MODELLING OF THE PRESSURE TUBE

From [1] 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 modelled fuel bundle is shown in the figure

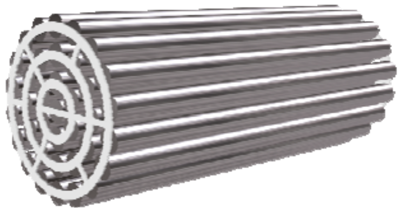

Fig 2: Modelled Fuel bundle in CATIA-V5

Fig 3: Modelled Pressure Tube in CATIA-V5

There are total of 380 such pressure tubes forming the core of a nuclear reactor, through which heat addition takes place. The modelled pressure tube is imported to ANSYS-CFX for the analysis using different fluids.

III. VALIDATION OF THE PROBLEM

The pressure tube imported is solved in ANSYS-CFX using Heavy Water as the working fluid and compared with the existing results [3]. The property values of the Heavy Water are taken from [4] & [5], the boundary conditions applied are taken from [1] and their values are given in table 1 and 2 respectively.

TABLE I. Properties of Heavy Water

Property	Value
Molar Mass (g/mol)	20.0276
Critical Temperature (K)	643.89
Critical Pressure (MPa)	21.67
Critical Volume (cm^3/mol)	56.3
Acentric Factor	0.364
Boiling Point (K)	374.57

TABLE 2. Boundary conditions for the pressure tube using Heavy Water

Boundary Condition	Value
Operating Pressure (MPa)	10.5
Outlet Pressure (MPa)	0
Mass Flow inlet (kg/s)	23.9
Inlet Temperature (K)	539.15
Heat Flux (per bundle) (MW)	9.6

The ANSYS-CFX result using Heavy Water matches well with the existing results. The comparison and the error percentage is given in table 3.

TABLE 3. Comparison of outlet parameters for validation

Property	Values from analysis	Values from [3]	Error Percentage
Inlet Pressure (MPa)	11.0529	11.04	0.117
Outlet Temperature (K)	586.975	583.15	0.656
Density at Inlet (kg/m^3)	795.607	782.9	1.62
Density at Outlet (kg/m^3)	699.442	692.4	1.017

With reference to the above table present model is considered to be validated.

IV. Analysis using Supercritical Carbon-dioxide

The validated model of the pressure tube is now used to do the analysis using Supercritical Carbon-dioxide as the working fluid. The property values of the Supercritical Carbon-dioxide are taken from [4] & [5].

The property values which are given as input in ANSYS-CFX is represented in table 4.

TABLE 4. Properties of Supercritical Carbon-dioxide

Property	Value
Molar Mass (g/mol)	44.01
Critical Temperature (K)	304.1282
Critical Pressure (MPa)	7.3773
Critical Volume (cm^3/mol)	94
Acentric Factor	0.22394
Boiling Point (K)	194.75

The boundary conditions applied for the analysis are given in table 5.

TABLE 5. Boundary conditions for the pressure tube using Supercritical Carbon-dioxide

Boundary Condition	Value
Operating Pressure (MPa)	7.5
Outlet Pressure (MPa)	0
Velocity Inlet (kg/s)	5.83622
Inlet Temperature (K)	300
Heat Flux (per bundle) (MW)	9.6

The model is solved using UPWIND Scheme.

V. RESULTS

After the completion of the analysis for the convergence criteria of 1e-05, the results obtained using carbon-dioxide as the working fluid are analysed by plotting different contours and different property parameters are compared with the results of the analysis using D_2O as the working fluid.

A. Contours

Various contours have been drawn at the cross-section of the fuel bundle and between the fuel bundles

1) Contours at the fuel bundle:

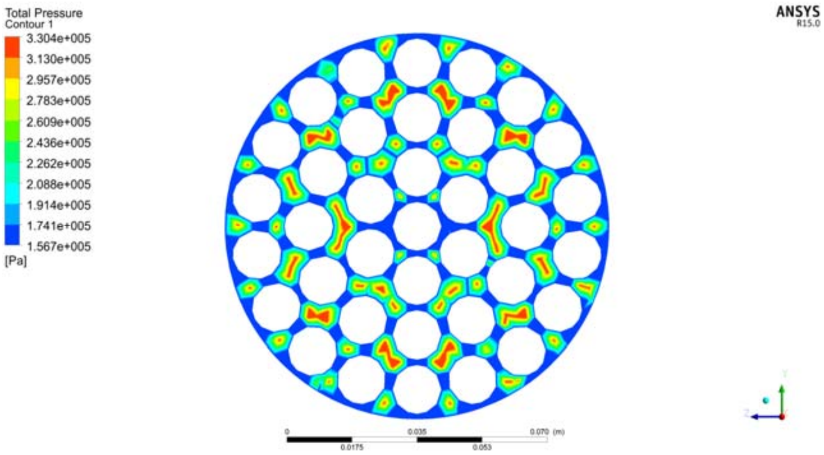

Fig 4: Pressure contours at the fuel bundle

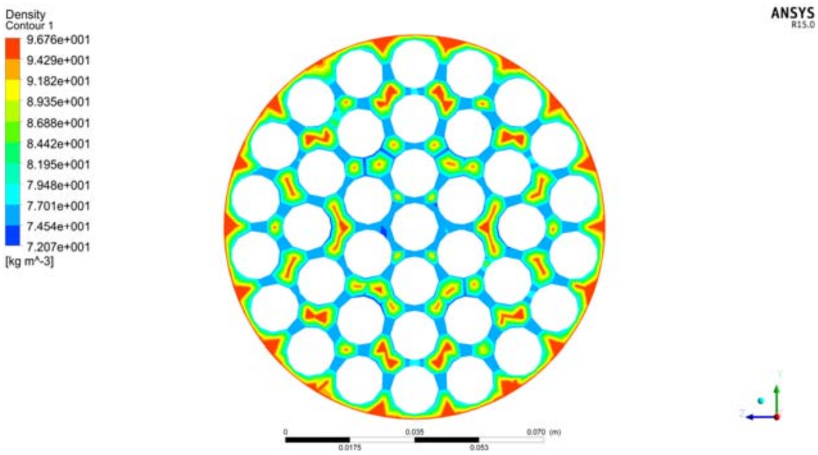

Fig 5: Density contours at the fuel bundle

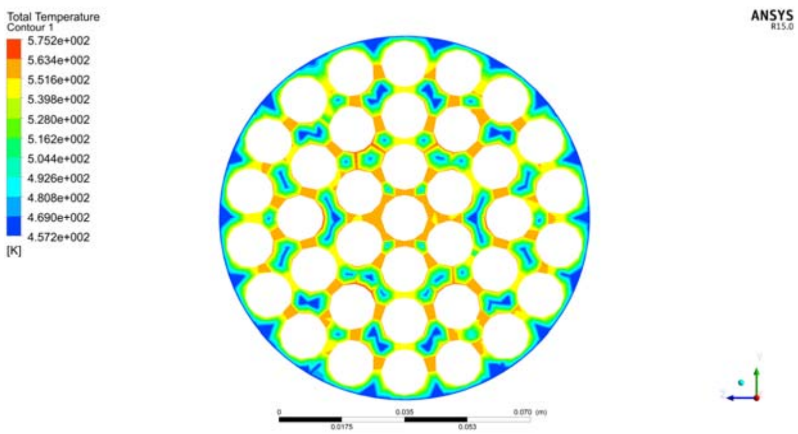

Fig 6: Temperature contours at the fuel bundle

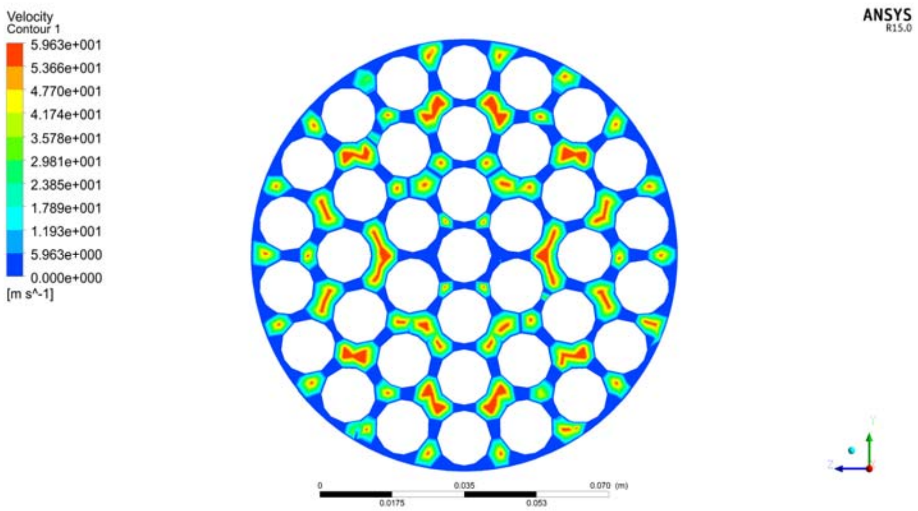

Fig 7: Velocity contours at the fuel bundle

2) Contours at the gap between fuel bundles:

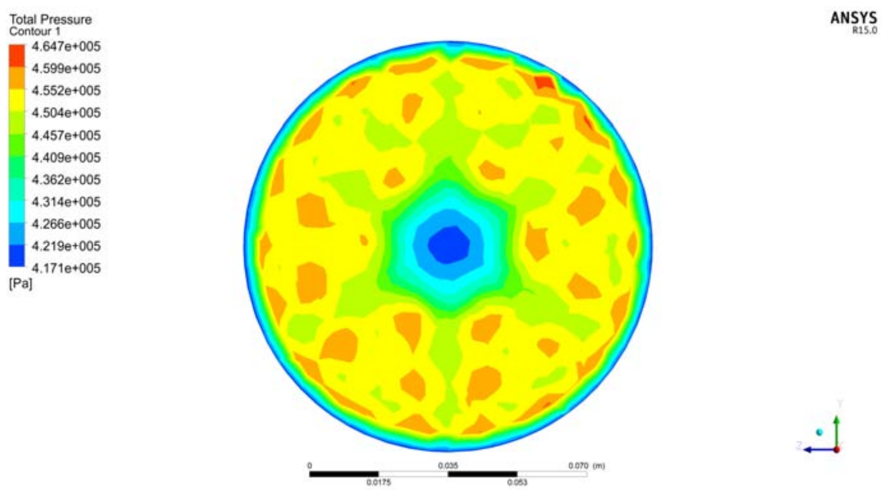

Fig 8: Pressure contours at the gap between fuel bundles

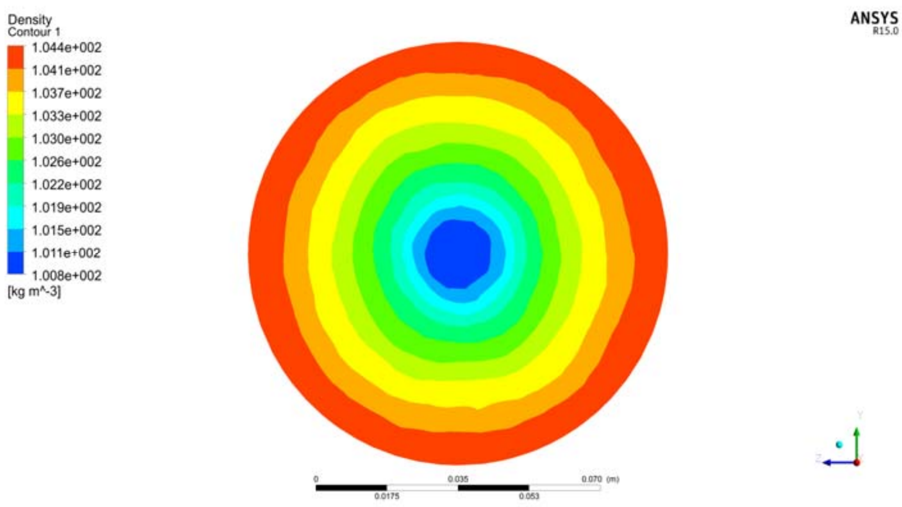

Fig 9: Density contours at the gap between fuel bundles

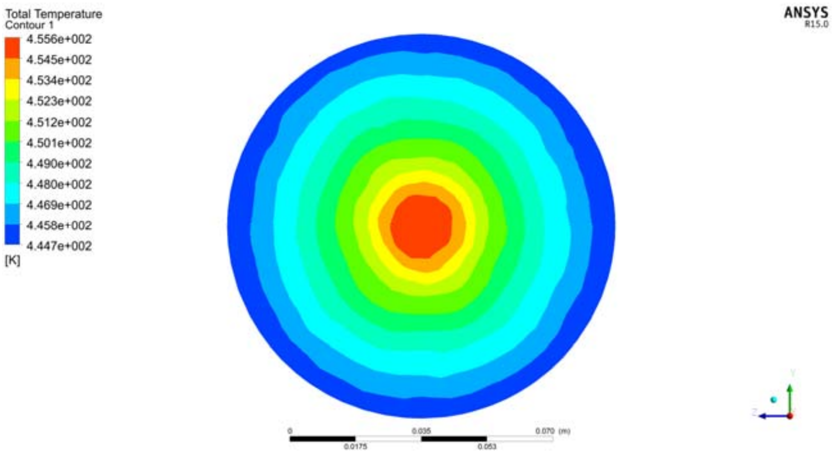

Fig 10: Temperature contours at the gap between fuel bundles

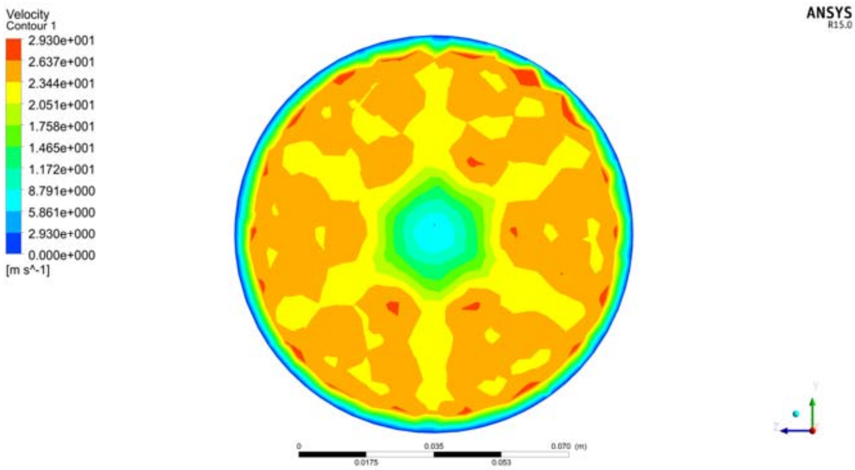

Fig 11: Velocity contours at the gap between fuel bundles

B. *Graphs*

Various graphs are drawn comparing the results of the analysis of the pressure tube with Carbon-dioxide and Heavy water as the working fluids.

1) For one fuel bundle (12th bundle):

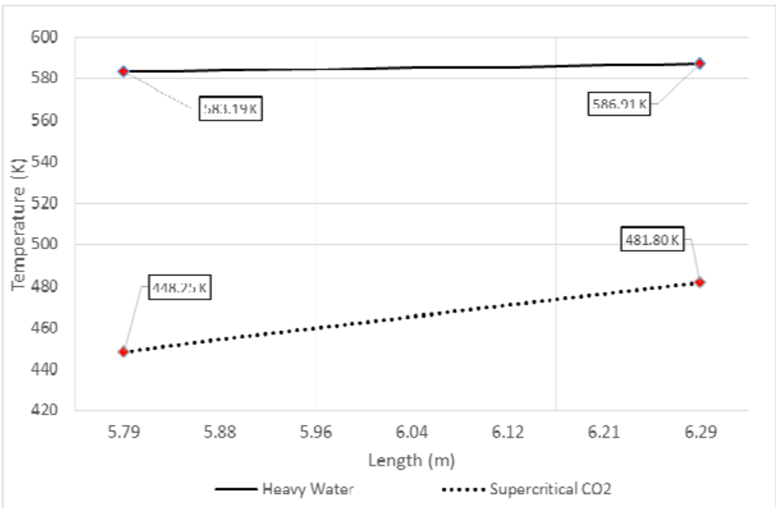

Fig 12: Graph between Temperature Vs Length for the 12th bundle

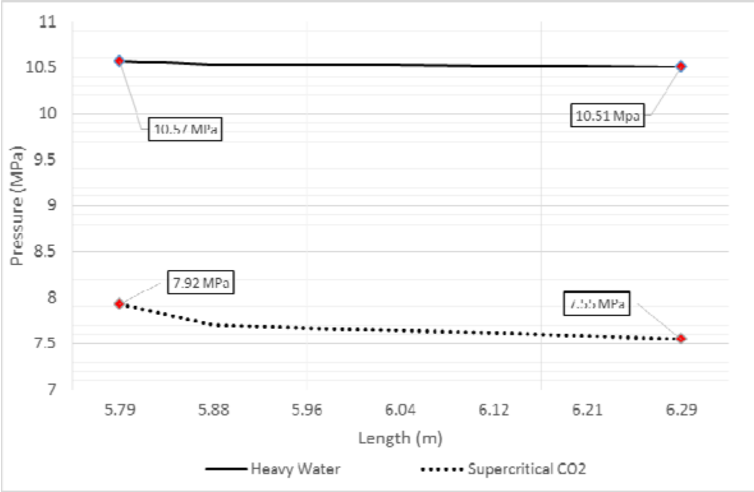

Fig 13: Graph between Pressure Vs Length for the 12th bundle

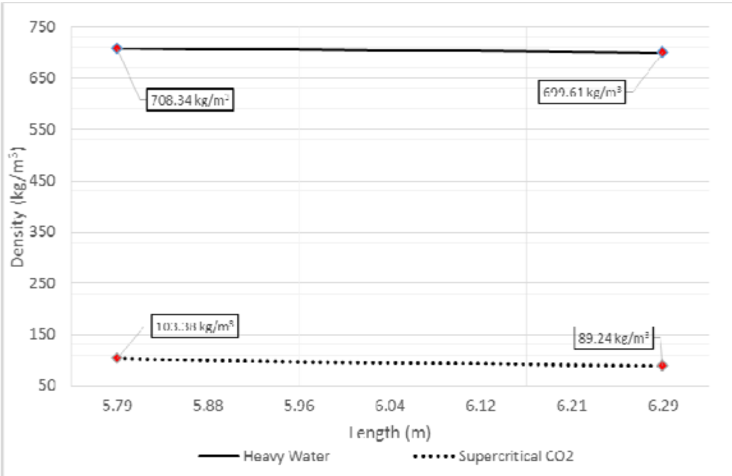

Fig 14: Graph between Density Vs Length for the 12th bundle

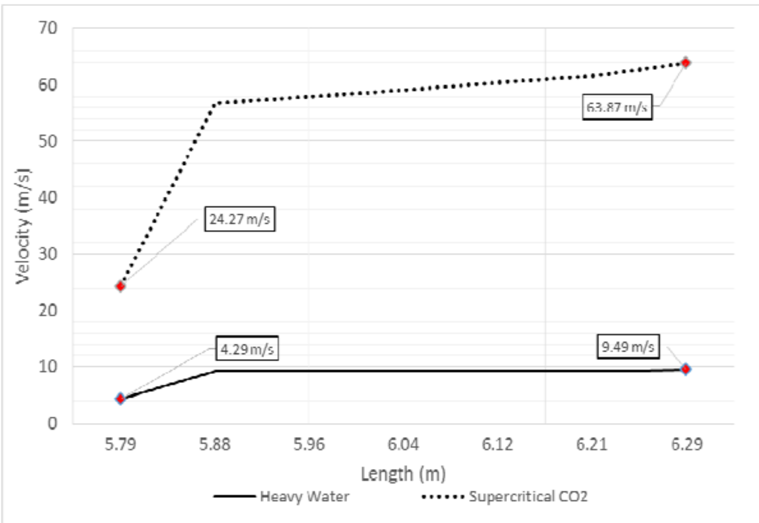

Fig 15: Graph between Velocity Vs Length for the 12th bundle

2) For the total pressure tube:

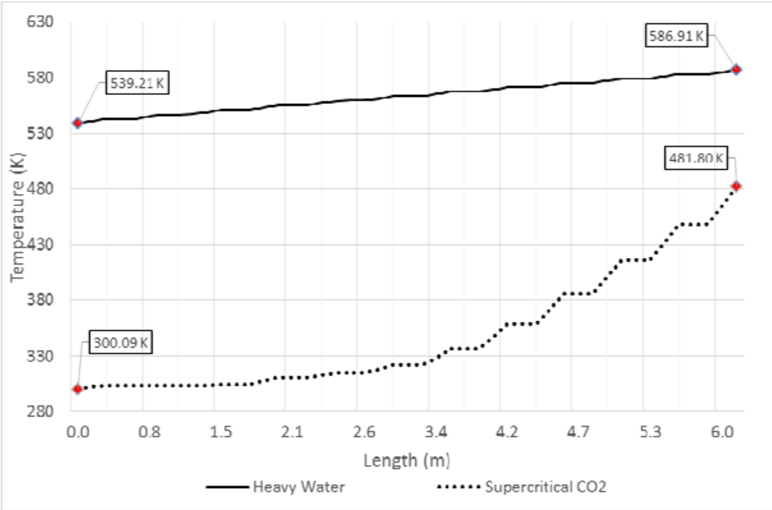

Fig 16: Graph between Temperature Vs Length for the total pressure tube

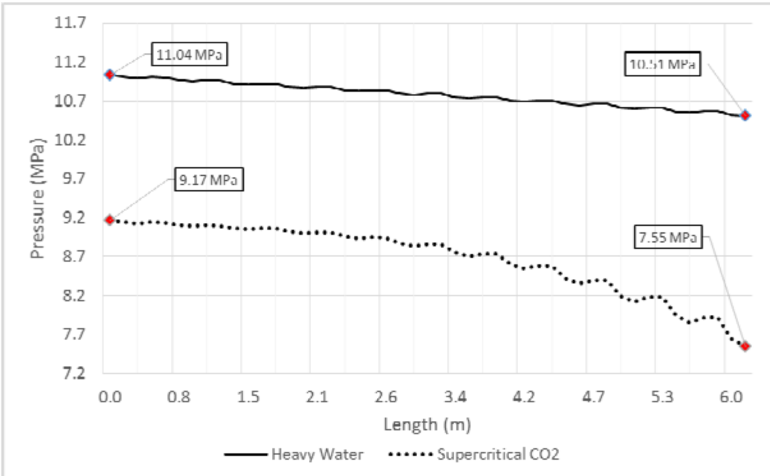

Fig 17: Graph between Pressure Vs Length for the total pressure tube

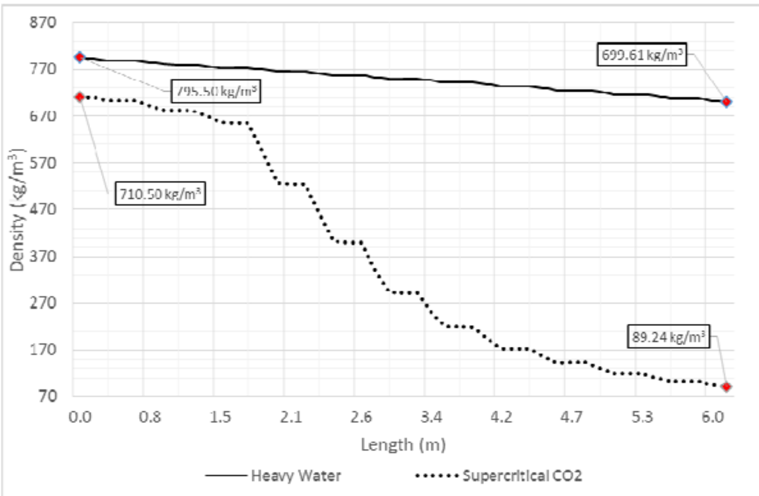

Fig 18: Graph between Density Vs Length for the total pressure tube

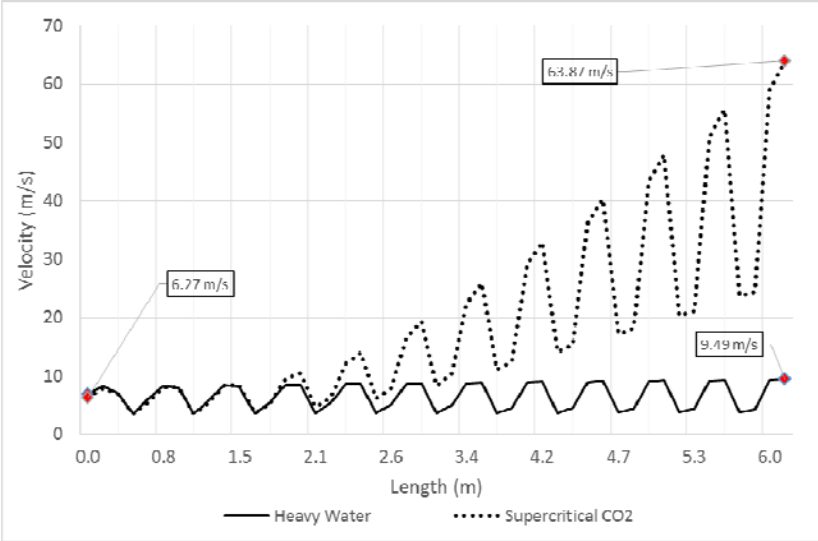

Fig 19: Graph between Pressure Vs Velocity for the total pressure tube

C. Variation of different properties for the pressure tube using Supercritical Carbon-dioxide

Variation of some of the other properties with respect to the length of the pressure tube are plotted below.

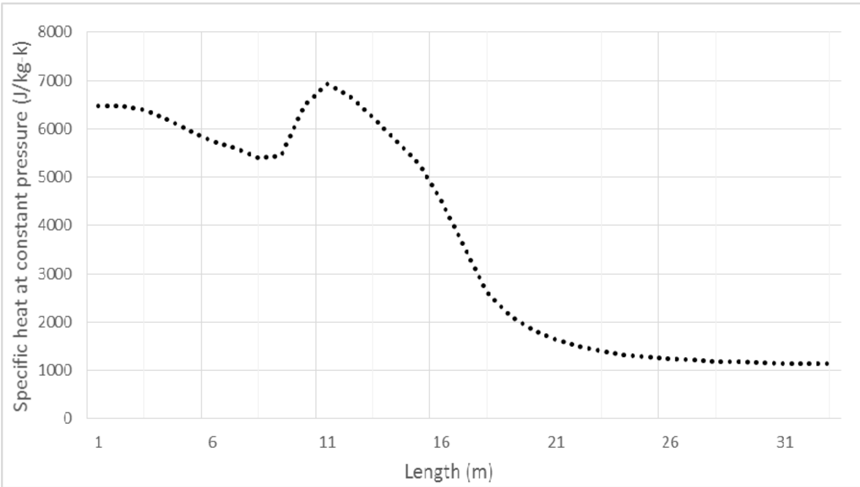

Fig 20: Graph between Specific heat Vs Length for the total pressure tube

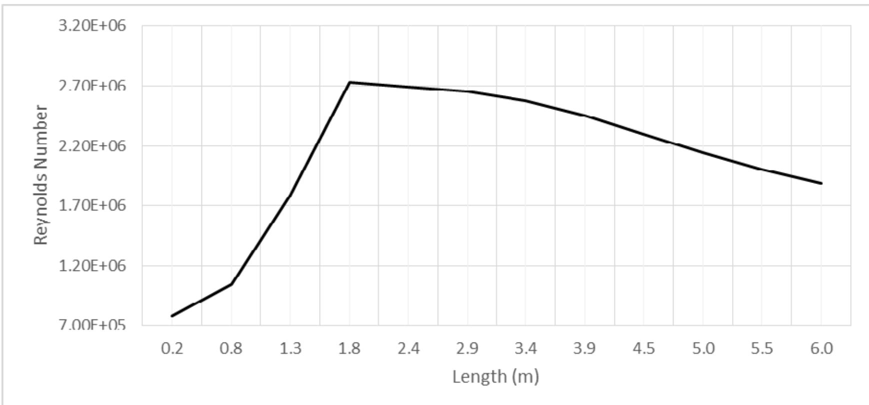

Fig 21: Graph between Reynolds number Vs Length for the total pressure tube

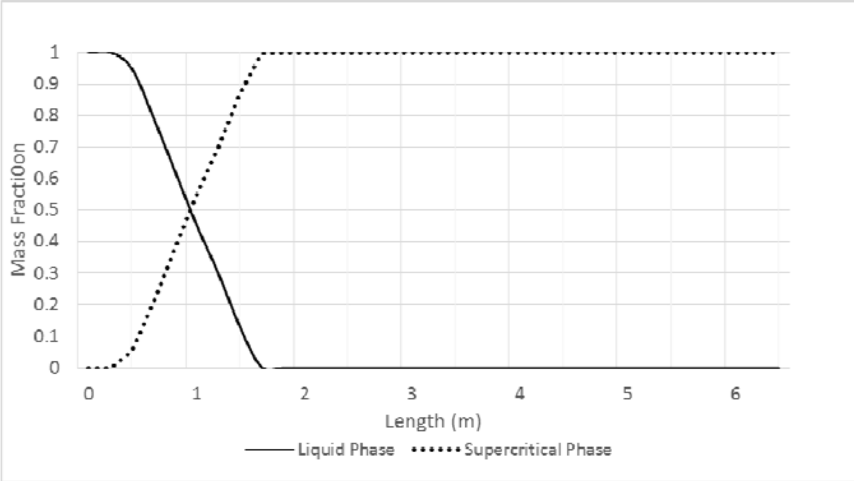

Fig 22: Graph between Mass fraction Vs Length for the total pressure tube

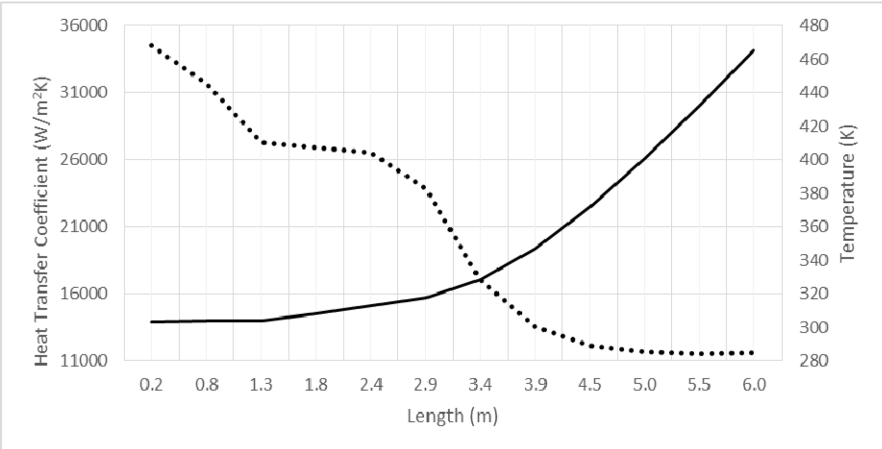

Fig 23: Graph between Heat Transfer Coefficient Vs Length for the total pressure tube

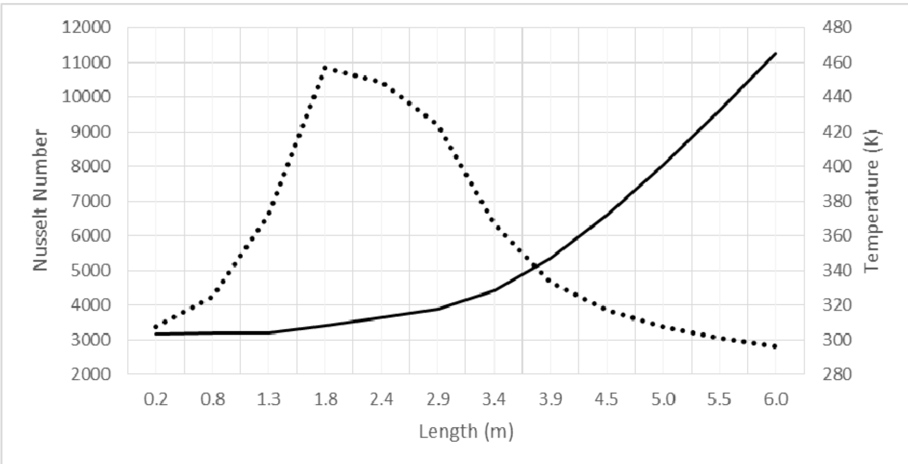

Fig 24: Graph between Nusselt number Vs Length for the total pressure tube

VI. CONCLUSION

The model of the pressure tube of CANDU 6 Nuclear Reactor created in CATIA V5 is validated with very less error percentage.

With reference to the analysis using Supercritical Carbon-dioxide as the working fluid, more amount of heat transport is done when compared to Heavy Water as the working fluid. In effect the capacity of the Nuclear Reactor can be increased for more power generation. From the fig 18 we can observe that density at outlet of the pressure tube is reducing greatly in case of Carbon-dioxide. Because of this, the mass flow rate is reduced which in turn reduces the size of pump.

Even though more pressure to be controlled using Supercritical Carbon-dioxide when compared to Heavy Water, mass flow rate of the working fluid is getting reduced for the same inlet velocity. So Supercritical fluids show a vast scope of research in future nuclear reactors.

REFERENCES

[1] Wm. J. Garland, “A text book on the CANDU Nuclear Power Plant Technology”, The Essential CANDU, ISBN 0-9730040.
[2] Dr. Robin Chaplin, “Genealogy of CANDU Reactors,” The Essential CANDU, Chapter 2, ISBN 0-9730040, Dec., 2016.
[3] 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.
[4] NASA Polynomial format for CHEMKIN-II, GRI-Mech Version 3.0 Thermodynamics released 7/30/99.
[5] http://webbook.nist.gov/, @2016.
[6] 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.
[7] K. Podila, Y.F. Rao, “CFD analysis of flow and heat transfer in Canadian supercritical water reactor bundle,” ELSEVIER, 2014.
[8] 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.
[9] 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.
[10] 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.
[11] 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.
[12] 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.
[13] 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”.
[14] 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 CO_2 heat transfer”.
[15] 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”.
[16] 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”.
[17] 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”.
[18] 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”.
[19] 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”.
[20] 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.
[21] 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.