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CFD-Based Steady State Analysis of an Optimum Working Fluid for Natural Circulation Loop in Nuclear Power Plant

*Joydeep Paul, #Abhra Bhattacharyya

*Student, *,#Department of Mechanical Engineering, Budge Budge Institute of Technology,

Affiliated to Maulana Abul Kalam Azad University of Technology, Kolkata West Bengal, India,

*joydeeppaul639@gmail.com, #abhrabhattacharyya99@gmail.com

Abstract: A rectangular 3-D model of NCL(Natural circulation loop) has been created. Steady State CFD (computational fluid dynamics) analysis is performed for the loop, using standard fluid solver codes. Single phase, supercritical phase analysis of various priory investigated working fluid , like CO_2 and water, under different pressure and temperature conditions has been conducted for a comparative analysis and study of the thermo-physical characteristics of the working fluids. On the basis of which, effective thermo-physical properties of an ideal working fluid in NCL, required for the optimum heat exchange, in average operating condition of a nuclear power plant has been stated and concluded.

Keywords — Steady State Analysis, Natural Circulation Loop(NCL), Critical Temperature, Velocity, Temperature Distribution, Pressure Gradient, Density, Nuclear Power Plant, CFD-based Analysis.

I. INTRODUCTION

Natural circulation loop is an heat exchanging device which can be used as an alternative of other heat exchanging devices(like fins) due to its simplicity and economical efficiency. NCL works on the principle of natural convection and the flow is driven by thermally induced density gradient leading to pressure gradient. NCL with simple geometry constitutes a heat source and a sink connected by adiabatic sections, where sink is placed at comparatively higher elevation. Application of NCL is diverse, but broadly it is used in nuclear power plant. One can use a NCL based device to give a nuclear power plant some urgent minutes that it needs in times of emergency. One can use the fluid inside the loop to act as cooler in times of need.

For near about five decades, number of researches took place in this field and emerging concept is that of Supercritical NCL with the emergence of Supercritical water reactor(SCWR). In SCWR, water is the primary working fluid although CO_2 for its non toxic and non explosive behavior ,along with its remarkable heat transfer performance, has led the way of consideration of CO_2 as next generation coolant. Lorentz and Paterson et al.[1] reported that use of CO_2 is safe, economical and environment friendly which redirected research towards it. Also, some other researches took place with CO_2 as the primary working fluid in different operating conditions. Kumar et al. [2-3] worked on 1-D steady state analysis of a rectangular NCL with end heat exchangers at low temperature conditions; neglecting the wall interactions of fluid and uniform consideration of fluid and flow properties like temperature, velocity etc. in radial direction of loop, hence which can be stated as oversimplified analysis to reveal the real or true fluid flow field behavior of working fluid. Vijayan et al.[6] performed experimental analysis on singke phase steady state on NCL with heater and heat exchanger. Yadav et al [4-5] reported the temperature contours and velocity distribution profile of 3-D simulations of CO_2 based NCL with heat exchangers. Also Yadav, Wahidi and Nagrani et al [5] performed steady state CFD simulation on 3D model of CO_2 and water based rectangular NCL with heater and heat exchanger as source and sink respectively. The analysis concluded that Reynolds and Nusselts number of CO_2 based NCL is higher than water based NCL. Cao and Zhang [6] analyzed the influence of heat sink temperature and inclination angle of the loop on the convective motion and heat transfer performance. Chen et al. [7] studied the effect of variable source temperature on the flow transition and instabilities of the flow system by keeping the sink temperature constant. Sarkar and Basu et al. [8] using carbon dioxide and water as a working fluid in NCL, 3-D numerical model for a rectangular NCL has been developed and investigated with CO_2 and water as working fluid under identical operating conditions. Magnitude of velocity is higher for

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the CO_2 loop than the water loop under all operating conditions considered, which can be attributed to the lower density value of the supercritical fluid. Due to effect of buoyancy across the horizontal sections, asymmetric variation can be found in both velocity and temperature profiles. Highest temperature across any horizontal section can be found near the top wall. Heat transfer coefficient is increasing for transcritical CO_2 and decreasing for supercritical CO_2. But it remains nearly constant for water as source or sink temperatures are changed. After detailed survey on all the relevant literature on CO_2 and water-based, single phase and supercritical phase NCL, it has been observed that works on the analysis of an optimum working fluid with desirable thermo physical properties for effective heat exchanging capabilities for its application in nuclear power plant is sparse. In the present study, efforts has been put forward to identify the optimum thermo physical properties of an working fluid with high heat exchanging capabilities at average operating condition of a nuclear power plant; by putting light into the comparative study and analysis of 3-D steady state analysis of rectangular NCL loop with water and CO_2 based working fluids.

Nomenclature:

C_p	Specific Heat (J/kgK)
D	Diameter (m)
g	Gravitational Acceleration (m/s²)
h	Enthalpy (J/kg)
H	Height (m)
k	Turbulent Kinetic Energy (m²/s²)
L	Length (m)
$\dot{m}$	Mass Flow Rate (kg/s)
p	Pressure (MPa)
p'	Modified Pressure (MPa)
P	Wetted Perimeter (m)
Pr	Prandtl Number
S_E	Source of Energy (W/m³)
T	Temperature (K)
u	Velocity (m/s)
x	Co-ordinate Direction
λ	Thermal Conductivity (W/mK)
ρ	Density (kg/m³)

II. METHODOLOGY AND ANALYSIS

A. Assumptions

In order to perform Computational Fluid Dynamics analysis for an optimum working fluid in NCL and comparative study of Co_2 and water based NCL, the following assumptions are made

1) Thermal properties of all fluid streams are uniform and constant

2)3D Steady state ,

3) No slip condition,

4) Axial conduction and viscous dissipitation are neglected

5) Minor losses due to bending and fatigue are neglected

6) Hot and cold stream are in single phase with constant heat capacity rates

7)Interaction of the fluid with the solid wall is neglected.

B. Formation of Geometry and Grid Generation

A three dimensional rectangular NCL is drafted for the purpose of analysis, which is shown in the Figure 1.Source and sink sections are located at the opposite horizontal arms and the vertical arms are assumed to be ideally insulated. Both source and sink are considered to be isothermal and influence of variations in source and sink temperatures is investigated. The pressure of the system is chosen in such a way that CO_2 achieves supercritical condition, while water remains in liquid state. Dimensions of the loop are as followed:- D= 15 mm, H= 1.25m, L= 1.46 m and L_{source} (L_h)= L_{sink} (L_c) = 1.2 m (Figure 1).

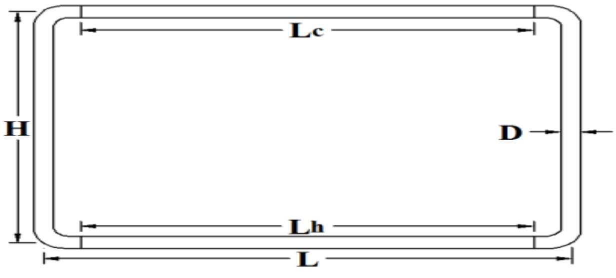

Figure 1. SCHEMATIC DIAGRAM OF THE LOOP

Mesh is generated for the geometry to serve the purpose of analysis ,of the following type - Quadratic type of element order is used and element size is 9.7163mm.Which can be seen in the figure 2 and 3 ,

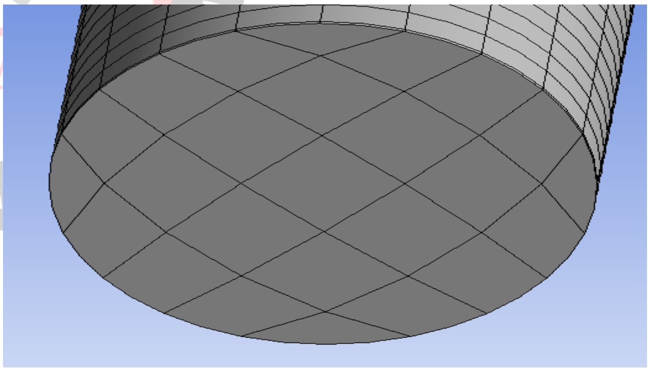

Figure 2: Cross section of the Meshed loop

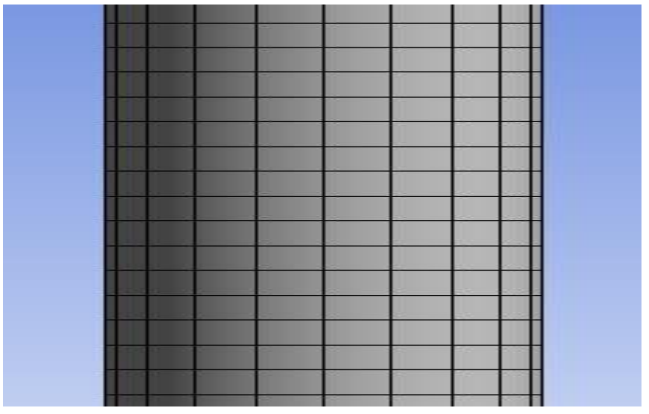

Figure 3: Transverse section of the meshed loop

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C. Governing Equations and Thermo-Physical property Calculation

The Governing differential equation of the flow field are as followed

1) Mass Conservation or Continuity Equation(1)

2) Momentum Conservation Equation(2,3a,3b,3c)

3) Energy Equation(4,5)

The governing differential equation of the flow field are three dimensional and independent of time i.e. , steady state.

Steady-state continuity equation:

$$\frac{\partial}{\partial x_j}(\rho u_j) = 0 \quad (1)$$

Steady-state momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_j u_i) = -\frac{\partial p'}{\partial x_i} + \frac{\partial \tau_{ji}}{\partial x_j} + \rho g_i \quad (2)$$

Here Modified pressure (p') and shear stress (τ_{ji}) are defined as:

$$p' = p + \frac{2}{3}\rho k + \frac{2}{3}\mu_t \frac{\partial u_j}{\partial x_j} \quad (3a)$$

$$\tau_{ji} = \mu_{eff}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_j}{\partial x_j}\right) \quad (3b)$$

$$\mu_{eff} = \mu + \mu_t = \mu + C_\mu \rho \frac{k^2}{\varepsilon} \quad (3c)$$

Steady-state energy equation:

$$\frac{\partial}{\partial x_j}(\rho u_j h) = \frac{\partial}{\partial x_j}\left(\lambda_{eff}\frac{\partial T}{\partial x_j} + u_j \tau_{ji}\right) + S_E \quad (4)$$

Where,

$$\lambda_{eff} = \lambda + \lambda_t = \lambda + \frac{C_p \mu_t}{Pr_t} \quad (5)$$

Pressure is chosen to be 10 MPa for both CO_2 and water. This particular pressure is below the critical pressure limits of water and hence calculation of water properties is quite simplified. However, critical pressure of CO_2 is 7.38 MPa, So CO_2-based NCL is operated under supercritical condition. Beyond critical pressure limit, thermo physical properties of any fluid are very sensitive with change of temperature.

III. Result and Discussion

As per the problem , that is discussed in above ,a computational model of the rectangular NCL is used for comprehensive investigation of the flow field and heat transfer behavior with both CO_2 and water as the working medium. The pressure of the system is chosen to be 10 MPa. The source and sink temperatures are limited to 371 K and 275 K each, which ensures that the CO_2 loop works as a transcritical to supercritical loop, whereas the water loop continues as a single-phase loop, despite they both are having identical boundary conditions. For similar temperature limits , CO_2 loop shows comparatively higher velocity values than the water loop. In some conditions, maximum source velocity can be 6 to 7 times larger than the CO_2 loop. Asymmetric variation in velocity can be observed across the cross-section in the presence of buoyancy field and centrifugal effect originating from the circulatory nature of the system. For the heater, velocity is higher near the bottom surface but for the cooler, same is higher close to the top .This type of asymmetric discrepancies is much more effective in the CO_2 loop, as nearly flat profile presented by the water loop . Critical temperature of CO_2 is near about 304.13 K. CO_2 operates in a supercritical system, for most of the source temperatures under consideration, which results in a very low density all over the loop. With increase in source temperature water density is decreased , leading towards such dissimilarities in both the magnitude of velocity and profile shape. The magnitude of velocity ,consistently increases with larger value of source temperature for both the loops, due to subsequent increase in difference between source and sink temperature. On analyzing both the loops with decrease in temperature of the sink, some discrepancy can be observed in terms of magnitude of velocity and nature of profile between CO_2 and water based loops. With decrement in sink temperature, difference in temperature across the loop increases, which results in increase in velocity of the liquids and the highest maximum velocity magnitude can be observed at lowest sink temperature level considered to be around 375 K. Due to very minimal changes in maximum density level of water, the profiles are very closely spaced, as per the analysis, within the present range of critical sink temperature. On the contrary, for CO_2 loop, with decrement in sink temperature, a brisk enhancement is observed in the magnitude of velocity but with further decrease in critical temperature, magnitude of velocity also drops rapidly. This anomaly can be explained by considering the rapid variation in fluid properties around pseudo- critical temperature(T_{pc}). 305 K is lower than T_{pc} at 10 MPa while 315 K is higher leading to increase in density of CO_2 . When the source side temperature is kept at 331 K, large density gradient between adiabatic arms increases the buoyancy force leading to increase in loop flow rate. With further decrease in critical temperature, density gradient falls rapidly and also the velocity magnitude drops rapidly. By keeping the sink temperature at 331k and critical temperature at 315 K, it is observed that the radial direction velocity (V_r) is having quite considerable variation, especially in the horizontal section. Also it is quite interesting to observe that the net flow is anticlockwise direction in water and clockwise direction in CO_2 in the loop under similar operating condition, which is one of the unique feature of NCL, where the direction of flow is quiet uncertain in advance and only after a complete CFD analysis, this can be evaluated. Temperature profiles at source and sink for both the loops are respectively with observed certain change in source temperatures 315 K. Water shows very little variation across the cross-section, particularly at low source temperature. But the CO_2 loop shows prominent variation, mainly at higher source temperature, with the lowest fluid temperature being lower than the wall temperature. Which is due to much larger change in the thermo physical properties of supercritical

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CO_2 across the tube. It is quite interesting to observe that lowest fluid temperature are near the bottom wall for the heater and highest temperature near the top wall for the cooler, which is the quite opposite trend as compared to velocity. Although, it is self explanatory, as the higher velocity fluid should have lower temperature due to less time for heat transfer and less buoyancy effect. It is an indication of a strong convective effect and similar nature of profiles can also be found with decreasing sink temperature. Variation of average fluid velocities with the location, due to different wall temperature patterns can be observed. So that the center plane of the adiabatic riser is selected as the target location. Increase the average velocities for both water and CO_2 with temperature, owing to the increase in temperature gradient. Average velocity of water briefly increases with decrease in the temperature difference while resultant buoyancy increases. CO_2 temperature increases quickly at the beginning and, when temperature drops below the critical temperature level ,it falls to a moderate level. Same kind of behavior has been observed prior instances as well, while discussing about the velocity profiles across the tube. The heat transfer behavior is analyzed in the form of estimation of average heat transfer coefficient at specific locations of the loop. Water exhibits much higher value of thermal diffusivity comparatively more than CO_2, which is definitely due to the higher value of thermal conductivity for the liquid phase than the gas-like supercritical fluid. Also the value of thermal diffusivity for water is nearly unchanged by the changing of source temperature. But the same for CO_2 drops a little bit. Changing of temperature from 331 K to 371 K causes thermal diffusivity to drop nearly to half. Which is the indication of the decrease in thermal conductivity of supercritical CO_2 at higher temperature. When the sink temperature is lower than that of critical temperature of CO_2, value of thermal diffusivity can be comparable to that of water. However, as sink temperature is increased above critical point, a steep fall in its value can be seen, displaying the significant change in thermo physical properties on either side of the critical temperature.

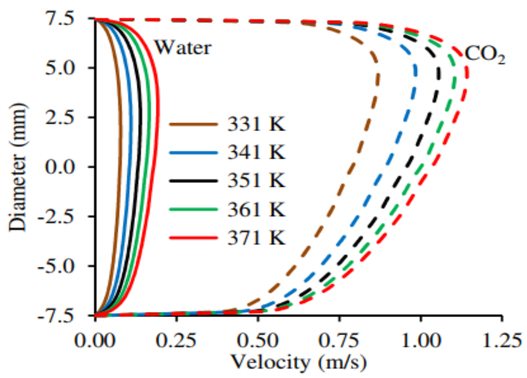

Figure 4:Velocity profile at sink centre for constant sink temperature of 315 K

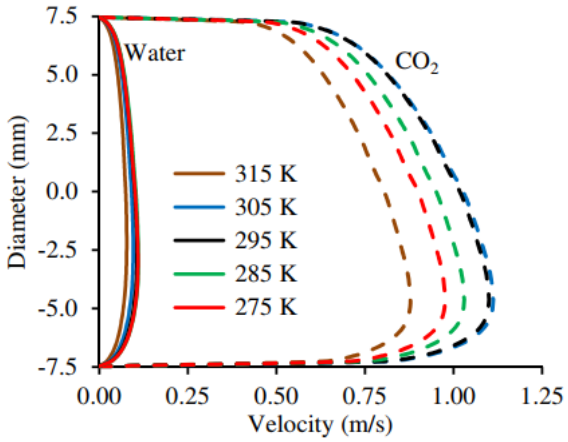

Figure 5: Velocity profile at source centre for constant source temperature 315 K

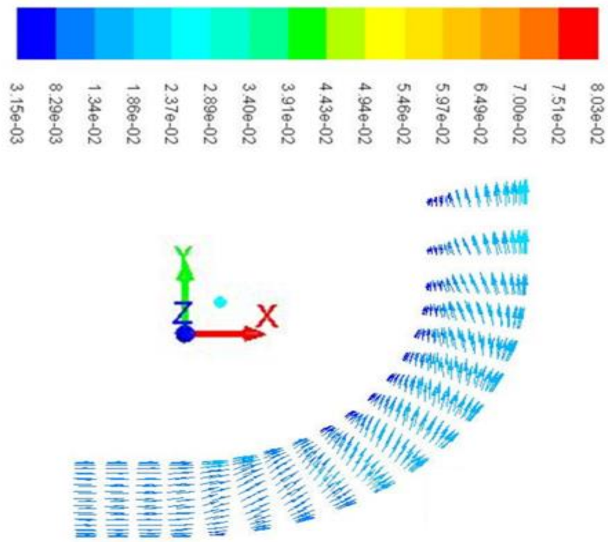

Figure 6: Velocity vector for water loop at a corner of bottom horizontal arm

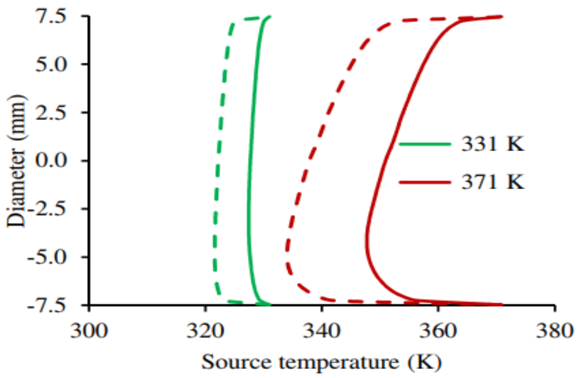

Figure 7: Temperature profile at source centre for constant source temperature at 315 K

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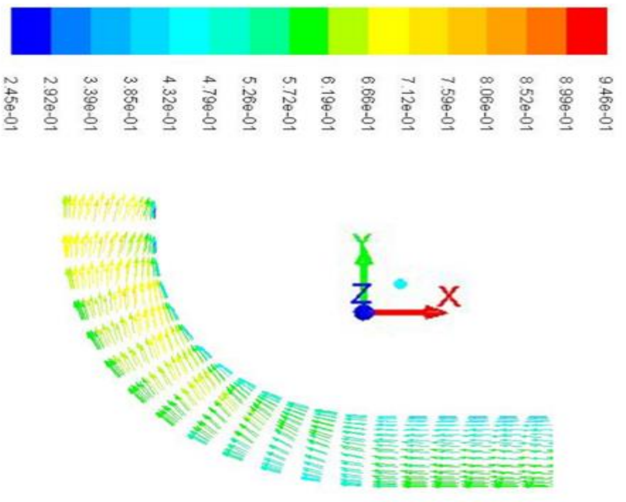

Figure 8: Velocity vector of CO_2 loop at a corner of bottom horizontal arm

IV. CONCLUSION

A three dimensional numerical model for a rectangular NCL has been generated and grid generation is performed for the purpose of the discretisation of the flow domain and comparative analysis of CO_2 and water as working fluid under similar operating conditions is performed. CFD analysis is conducted through ANSYS FLUENT, which uses Finite Volume Method(FVM) for the discretisation of the governing differential equations and perform iterative methods in order to converge to the solution with the desired range of accuracy. Operating conditions for the CO_2 loop is considered to be in supercritical phase while for the water loop to be in single phase. Under the consideration of isothermal heat source and sink comprehensive study of flow and heat transfer characteristics of both the fluids has been performed. Results of the analysis have been scrutinized and the following conclusions can be drawn regarding the comparative study and the desirable properties of an optimum working fluid operating under the average working conditions of a nuclear power plant are as stated below:-

1. Magnitude of velocity for the CO_2 loop is relatively higher than that of the water loop in all operating conditions which has been considered, that can be attributed to the lower value of density of the supercritical fluid.

2. As the effect of buoyancy is prominent across the horizontal sections, asymmetric variation can be observed in both velocity and temperature profiles. Maximum value of temperature across any horizontal section can be observed near the top wall. Heat transfer coefficient is increasing for transcritical CO_2 and decreasing for supercritical CO_2. But it remains nearly constant for water as source or sink temperatures are changed.

3. Although the operating temperature of coal power plant is much higher than that of nuclear power plant but it also need to be kept it mind that for thermal power plant the operating temperature is the highest achievable temperature of that plant. But for nuclear power plant there is no limit of achieving the highest temperature of nuclear power core. Since there is option for switching off the nuclear power core in an instant of time hence, it need to be provided with some kind of delaying device which can provide time so that the plant can be turned off. Hence, a working fluid used in NCL which is working in a nuclear power plant should not evade all of its thermo-physical properties as well as its fluid properties in a fraction of second so that one use it as a delaying device.

4. It also need to be considered that the working fluid used in NCL should not posses much higher values of density, as it can blow off the loop. Critical temperature(T_c) of the working fluid should be a bit higher than the operating condition temperature of the nuclear power plant so that it can be used in emergency purposes. The variation of the thermo-physical properties should not be steep near the pseudo critical temperature (T_{pc}) of the working fluid.

5. It also need to be kept in mind that NCL is rather an auxiliary back-up device then fulfilling the criterion of primary emergency device.

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