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Flow of Supercritical Carbon Dioxide through a converging-diverging nozzle

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ABSTRACT

Supercritical carbon dioxide (sCO_2) power cycles has the potential to offer higher plant efficiency than the traditional Rankine superheated steam cycle especially as the turbine inlet temperature is increased past ~500°C. Apart from others, one of the key aspects to achieving such improved efficiency is utilizing the high fluid density near the critical point to reduce the required compression work, and hence the back work ratio of the cycle. On the other hand, highly compressible nature and drastic property variations of fluid near the critical point gives rise to numerous practical challenges both in terms of design and operation of the sCO_2 compressors. This paper explores the flow of supercritical carbon dioxide through a converging diverging nozzle near the critical point. High speed shadowgraph images of the flow along with the pressure profiles were recorded and are presented for operating conditions near the critical point.

INTRODUCTION

Supercritical carbon dioxide power cycles are trending alternatives to the steam-generated power cycles due to attractive thermodynamic properties near the critical point. High specific heat and high density of CO_2 near critical point allow the volume of turbomachinery to be smaller than that used for superheated steam or helium [1]. However, use of carbon dioxide as a working fluid renders an issue of condensation near the critical point of the two-phase dome. High local velocity and pressure drop within the turbomachinery can lead to nucleation [2]. To investigate more on the nucleation process, converging-diverging nozzle was used to mimic the converging and expanding regions of turbomachinery. A computational study was done through 1-D isentropic flow calculations and 3D numerical simulations to observe any condensation effect and the associated pressure drop and density changes. Carbon dioxide is flown through this nozzle to observe condensation effects near the critical point. A high speed camera was used to capture the process of condensation. This paper aims to study the nucleation effects of sCO_2 in a converging-diverging nozzle through experiments and numerical investigation.

NUMERICAL INVESTIGATION

A 1-D isentropic model was used to predict the mass flowrate as a function of the throat pressure for the nozzle dimensions shown in Figure 1 [3]. The nozzle has a 3mm thickness. Figure 2 shows the graph of the mass flowrate as a function of the throat pressure for a given inlet pressure and temperature 7.73 MPa, 34.07°C respectively.

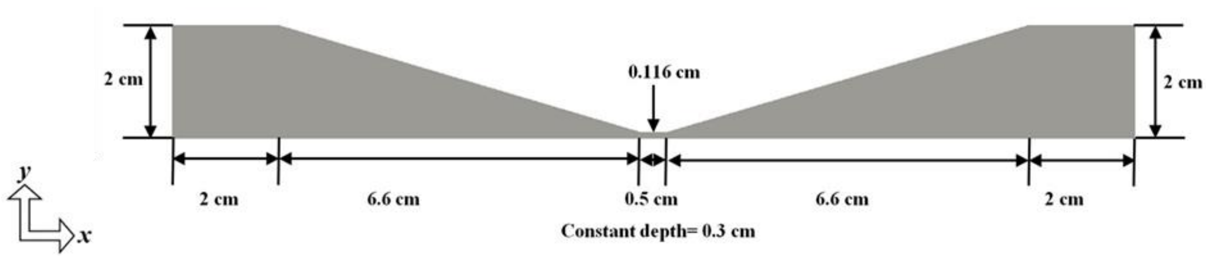

Figure 1: Dimensions of the converging-diverging nozzle used for numerical investigation

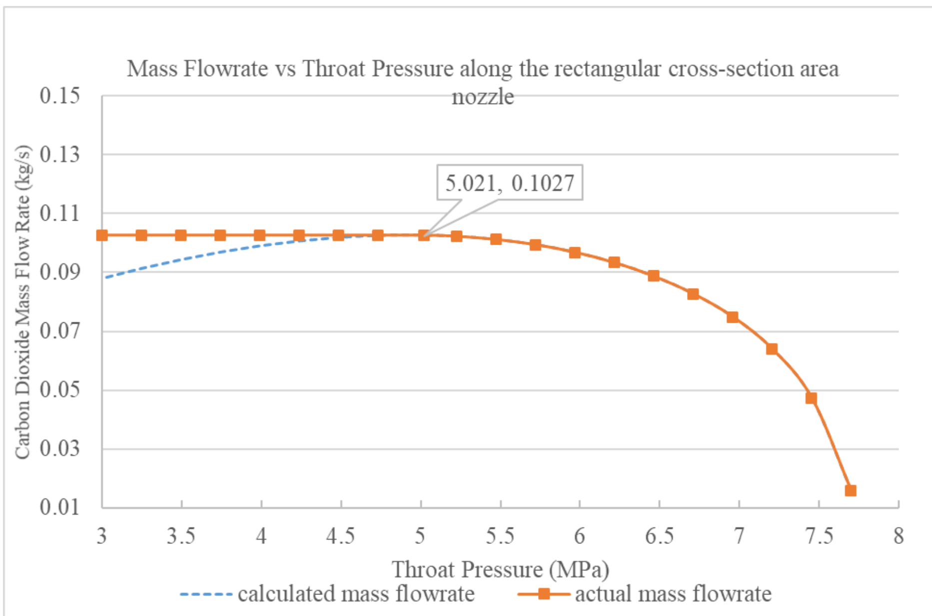

Figure 2: Mass flowrate versus throat pressure in a converging-diverging nozzle; Inlet pressure is 7.4 MPa and temperature is 34.07°C.

Note that the mass flowrate reaches maximum at throat pressure 5.021 MPa. Realistically, the mass flowrate should not decrease after 5.021 MPa throat pressure. The orange line in Figure 2 indicates the actual mass flowrate after throat pressure lower than 5.021 MPa. With preliminary experiments performed, it is observed that there is a pressure drop of 0.5 MPa after the throat. To show similar results with given experimental condition in 1-D isentropic calculations, mass flowrate corresponding to throat pressure of 7.23 MPa was used. With the mass flow rate of 0.065 kg/s, 1-D isentropic calculations were performed along the nozzle shown in Figure 3 [3]. Starting from top, the figure displays velocity, pressure, and quality along the nozzle.

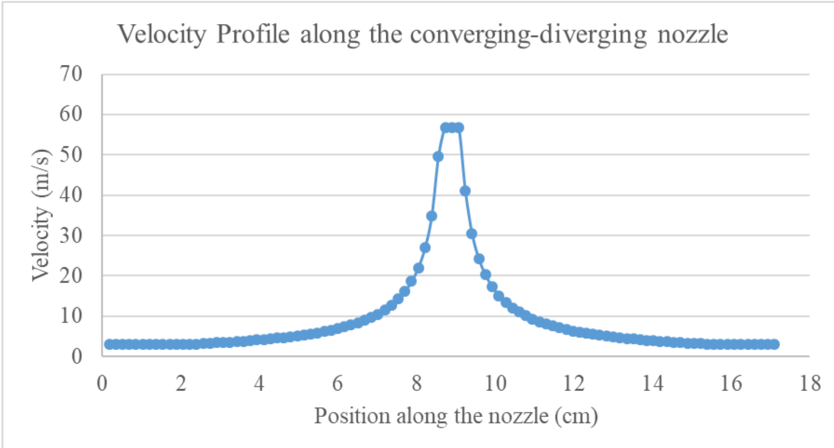

Figure 3a: Velocity Profile along the converging-diverging nozzle

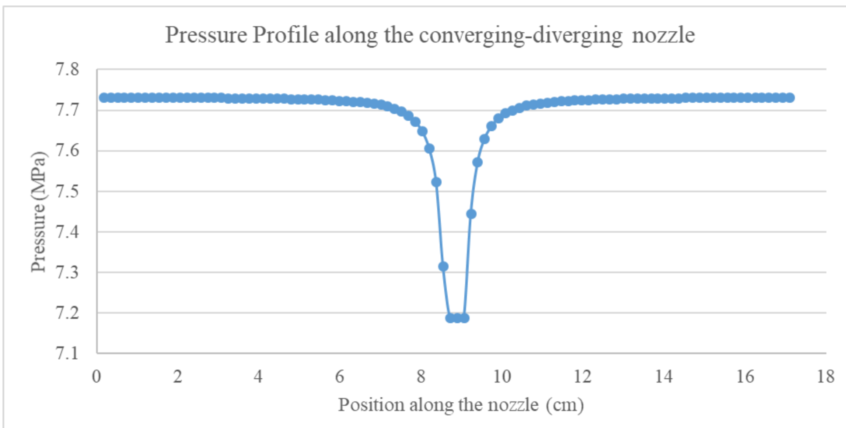

Figure 3b: Pressure Profile along the converging-diverging nozzle

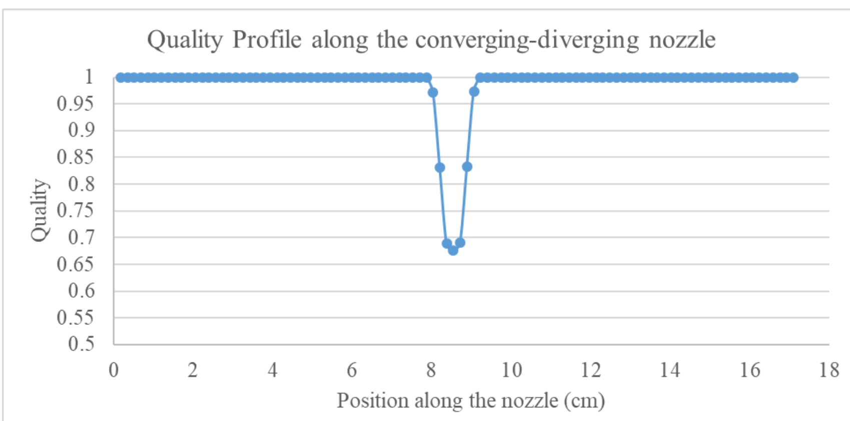

Figure 3c: Quality Profile along the converging-diverging nozzle

With 1-D isentropic calculations performed at 7.73 MPa and 34.07°C as the inlet condition, the velocity at the throat is expected to be 56.8 m/s. It is important to note that the pressure drops by more than 0.5 MPa at the throat. Quality at throat changes from the supercritical state to a mixture of carbon dioxide liquid and vapor, a firm indication of occurrence of nucleation at the throat.

A transient compressible 3D Navier-Stokes solver, coupled with continuity, and energy equations have been implemented to study the nucleation behavior in more detail. In order to expedite the simulations, Fluid property Interpolation Tables (FIT) based on a piecewise biquintic spline interpolation of Helmholtz energy have been integrated with OpenFOAM to model sCO_2 properties [4,5]. The mass fraction of vapor created in the venturi nozzle has been calculated using homogeneous equilibrium model (HEM). For Figure 4, the boundary conditions of the simulation are following: mass flow rate of 0.065kg/s, inlet pressure of 7.73 MPa, exit pressure of 7.28 MPa, and inlet temperature of 307.22 K. With given conditions simulation image was capture at 2ms. With this captured image of the simulation, average pressure and temperature are plotted along with venturi nozzle profile [6]. To distinguish different condensation behavior, central plane of the nozzle and end plane (along the window of test section) are distinguished in Figure 5.

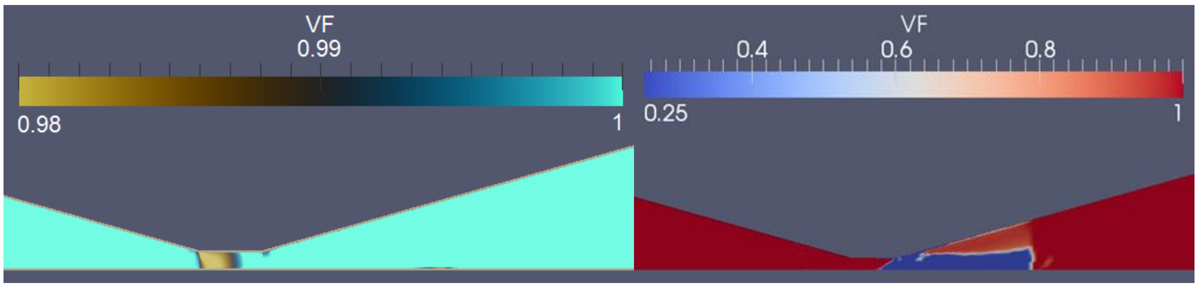

Figure 4: Simulation of Condensation Behavior at t=2ms for central plane (left) and wall (right)

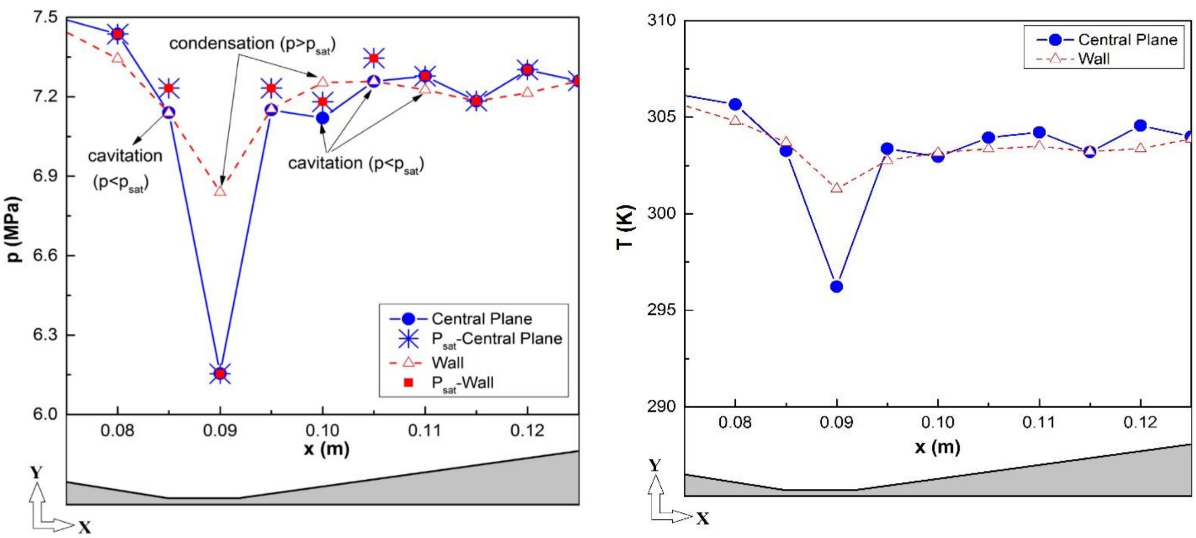

Figure 5: Average pressure (left) and temperature (right) in simulation of condensation behavior at t=2ms

EXPERIMENTAL INVESTIGATION

For visual interpretation, shadowgraph technique was used to capture the condensation along the throat of the nozzle. Using a 250W light source and a Photron SA-Z high speed camera recording video at 40,000 fps, a distinct condensation behavior was captured as shown in Figure 6. Figure 6 presents the snapshots at different times from the recorded video. It coincides with the simulation graph from Figure 4 that the initial condensation points are captured at the top corner of the venture nozzle and just after the throat. At later times, the condensation is pushed by the incoming carbon dioxide flow and is spread all over the diverging nozzle. With the given brightness and contrast, not only initial condensation points were captured but also the developing boundary layer at the throat inlet. As the time passes, a larger boundary layer is observed. With the high speed camera, the initial point of condensation occurs at the inlet of the pressure transducer just downstream of the throat region, which can be treated as one of the nucleation sites.

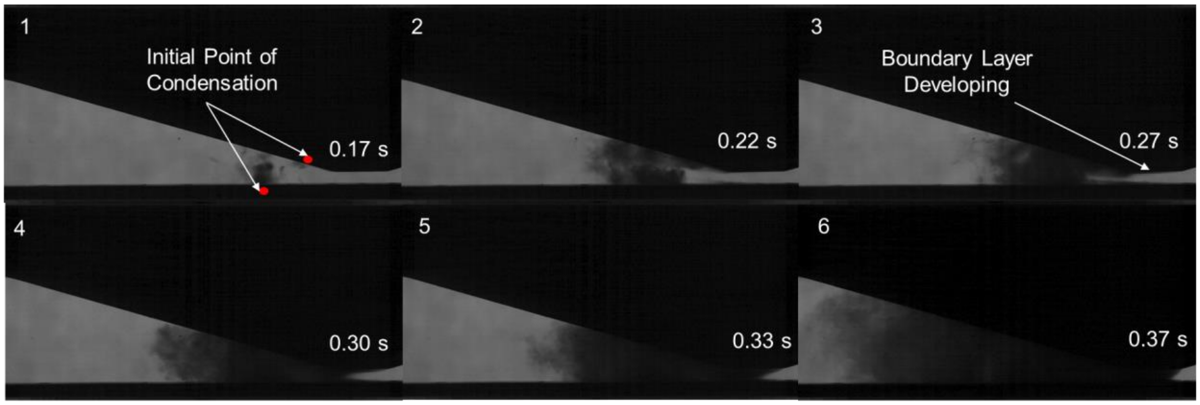

Figure 6: Condensation process captured through high speed camera at 40,000fps

CONCLUSION

Nucleation of carbon dioxide near critical point was studied through numerical simulation and high speed shadowgraphy technique. 1-D isentropic calculations were performed to find the appropriate mass flowrate, venturi velocity, pressure, and quality profiles. OpenFOAM was used to solve 3D transient compressible Navier-Stokes equation and energy equation along with carbon dioxide properties retrieved from Fluid property Interpolation Tables (FIT) based on a piecewise biquintic spline interpolation of Helmholtz energy. High speed camera was used to observe condensation behavior at 40,000 frames per second. Due to the sensitivity of temperature and pressure near the critical point, challenges still exist to precisely control the temperature and pressure at the inlet of the test section as well as the calculation of thermodynamic properties along the nozzle. More research is yet to be done with different nozzle geometries and other advanced diagnostic techniques to further study the condensation behavior.

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