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Experiments on Methane Injection Characteristics in Supercritical CO_2 Environment

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Abstract:

In the pursuit of efficient processes and power cycles, operating pressures have reached values exceeding the critical thermodynamic pressure in many applications. The Allam cycle (direct-fired sCO_2 cycle), whose operation is beyond the critical point of CO_2, is gaining the attention of industry, academia, and governments worldwide due to its remarkable promise of efficiency and environmental friendliness, and economical operation. This use of supercritical working fluids challenges our current understanding of injection processes and even the notion of 'multiphase' itself. We discuss an experimental investigation of injection for direct-fired supercritical CO_2 (sCO_2) combustors relevant for the sCO_2 Allam cycle. Specifically, we study methane injection into a chamber filled with CO_2 at various temperatures and subcritical to supercritical pressures. Unlike classical fuel injection, the jet has a much lower density than the background fluid. We analyze jet spreading and find good agreement with classical jet spreading theories validated for dense sprays. Also, we examine other jet flow characteristics of the injected jets pertinent to supercritical conditions by using the experiments.

Introduction:

The Allam cycle works in the direction of capturing the CO_2 and attaining high thermal efficiencies without losing the output power for compression. However, the pressure values are reaching beyond the critical pressure of CO_2 for generating high thermal efficiencies. For instance, the Allam cycle generates higher efficiency with 95% CO_2 dilution by working at an optimum pressure of 300 bar. Usage of supercritical CO_2 (sCO_2) power cycle is a new technology to accomplish that goal, and recently many fundamental studies were conducted in our lab to address various aspects of this cycle [1-24].

Jet mixing is a vital parameter that governs the thermal efficiencies of cycles. Furthermore, it characterizes the entrainment of fluid along the length of injection. Nevertheless, it is not being thoroughly investigated at these high-pressure values. The benefit of applying the supercritical conditions is extended by increasing the dissociation of combustion products. At these supercritical conditions, the fluid changes its normal behavior.

There are works in the literature that explain the vital role of jet divergence at subcritical to supercritical conditions. The first experimental study on the injection of CO_2 into the N_2 environment was reported by Newman and Bruzstowski [25]. The observed widening of jet profile and finely atomized spray at supercritical conditions. Author Mayer. et al. In a study [26] injected the LOX in gas phase hydrogen at maximum limiting pressure of 100 bar, and temperature ranging from 100 K to 370 K. Their results explicitly said that, at supercritical conditions, the jet will not be regarded as spray formation; instead, it is fluid/fluid mixing. Chehroudi et al. presented their findings [27] on round jet growth rates with the injection of N_2, O_2, and He into the chamber with several media including N_2, He, and mixtures of O_2/ N_2 at subcritical to supercritical conditions. Furthermore, they added a fluid structure that appeared like a classical liquid jet breakup at subcritical thermodynamic conditions. Whereas above critical values atomization is inhibited due to the vanishing effect of heat vaporization. The published literature showed that CO_2 behaves like gas in the subcritical region, whereas, in a supercritical regime, CO_2 has a gas structure but has a density like liquid. Consequently, the study jet mixing of CO_2 and methane is considered multiphase mixing.

As operating pressures reach high values, the experimentation becomes more challenging as it is costly and time-consuming. In addition, there is less understanding of jet mixing at higher thermodynamic conditions. Therefore, the current scenario necessitates the application of a simulation tool to simulate similar higher thermodynamic conditions. In the simulation tool, there is a requirement for experimental data for validation at such harsh thermodynamic conditions. Hence, the present letter reports experiments conducted with a methane injection in a chamber filled with CO_2 at subcritical to the supercritical environment. The experiments included were performed at CO_2 pressure ranging from 60 to 200 bar and a temperature of 90 C.

Experimental facility:

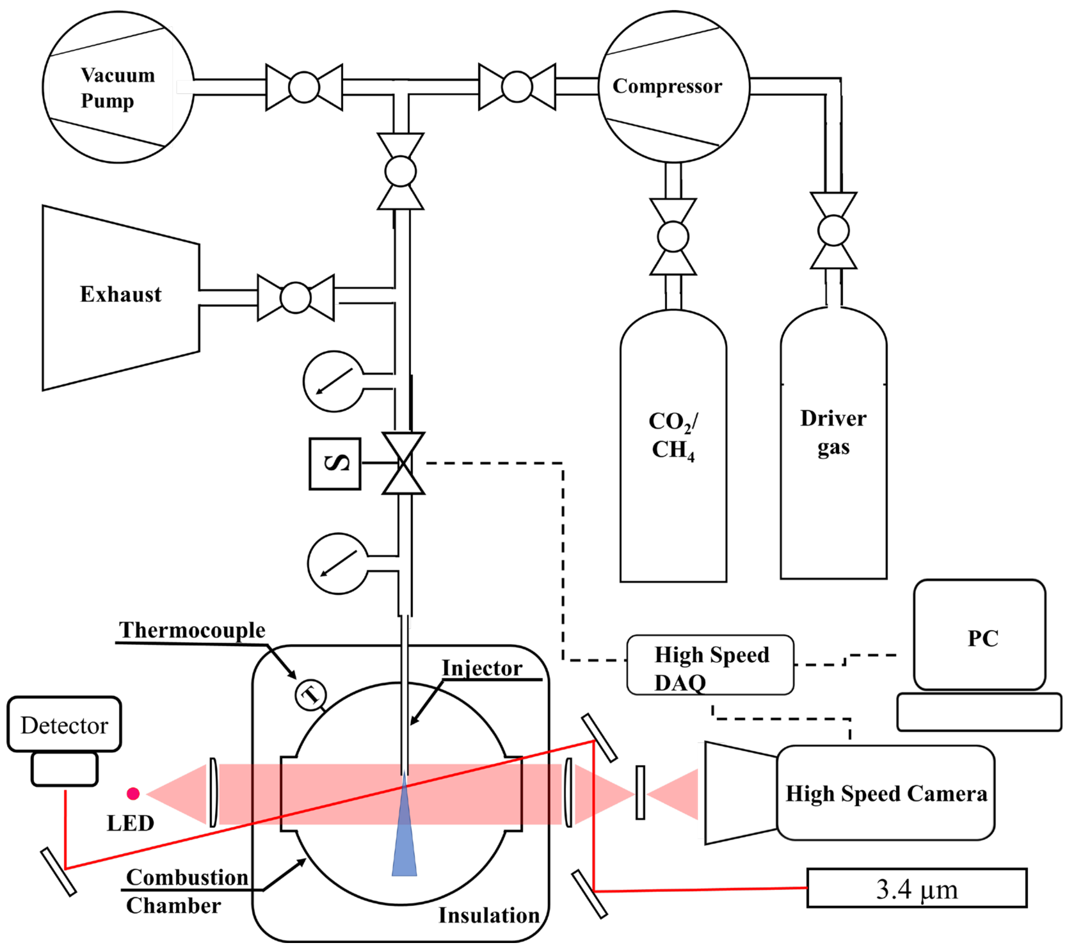


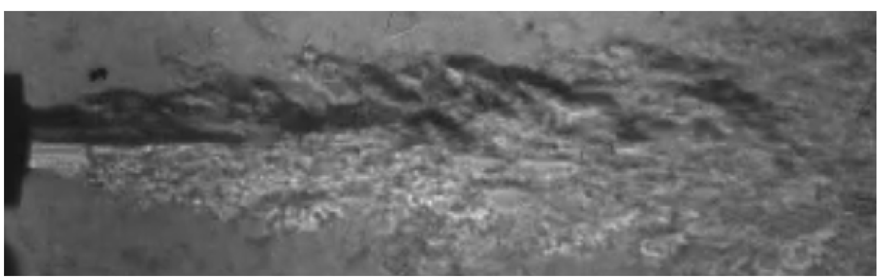
Figure 1: Detailed experimental construction facility

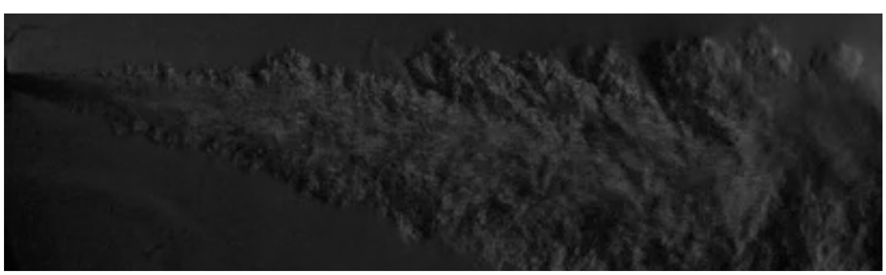
Experimental construction adapted in the current study is neatly represented in Fig.1. A similar experimental facility is briefly explained in the previous study. The constant volume stainless steel cylindrical rig withstands at a maximum bar pressure of 300 bar, enabling experimental measurement at the required pressure range. The chamber acquired two optical accesses with around 85% transmission for 3.39 μm laser light. They are made up of sapphire material and have a diameter of 3 inches. The chamber assembly is covered with an insulation box made up of foam material, and the box helped maintain the uniform chamber temperature. Two thermocouples were installed on the surface of the chamber to record the temperatures. The temperatures were averaged that represents the temperature of the chamber.

Result and Discussion:

The qualitative pictures which exhibit the thermodynamic transformation of injected methane into the CO_2 environment are illustrated in fig. 2. In fig.2.b injected flow is shown for supercritical thermodynamic conditions. In supercritical mixing, it is observed from the image that there is no more liquid atomization due to negligible surface tension, which suggests that the fluid behaves like a gas and the term liquid is no longer applicable for supercritical flow. As a result, ligament formations are considerably reduced. The characteristic disturbances can be seen from the wavy surface at the edges. In addition, generally, the liquid vanishes due to domination of the evaporation process due to latent heat of vaporization; however, in supercritical mixing, the jet is governed by mass diffusion rather than evaporation as the flow is in the gaseous phase. The mass diffusion strengthens the shear forces and dominates the capillary forces. Therefore, the jet mixing approaches gas/gas mixing at thermodynamic conditions exceeding the critical values.

a)





In fig.2.a, visualization of subcritical methane jet injected into subcritical CO_2 environment. From the phase diagrams, it is seen that both fluids behave like gas. Hence, there will be gas/gas jet mixing in the subcritical regime. Similar characteristic features apply to supercritical jet mixing, where the diffusion process dominates over evaporation and surface tension vanishes. Although jet approaches gas/gas mixing in subcritical and supercritical regimes, the density ratio of the jet in supercritical mixing is higher than in subcritical regimes. The reason is attributed to the two-phase behaviors of the jet in the supercritical regime, as stated previously. A detailed presentation of our results will be available in a future publication.

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