Characterization of jets under supercritical conditions

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1. Introduction

The suggestion to use supercritical fluids (SFs) is a century old, but the main progress in investigating and utilizing supercritical fluids has occurred mostly in the past 20 years [1]. They have been used (or proposed for use) as solvents, reaction media, processing media, and propellants. As example supercritical fluids can be effectively used in many industrial applications such as extractions (of vitamins, perfumes, etc.), syntheses, and processing steps. SFs are used to remove unwanted materials, such as caffeine and cholesterol from food products. They are also successfully used in many instances of analytical laboratory separations and ethane is one of the most used fluids for extraction and chromatography. SFs are now replacing organic solvents in industrial processes. Indeed, many of these solvents have adverse environmental and health effects and supercritical CO_2 or water are attractive alternatives because they are inexpensive and offer minimal threat to both the environment and human health. SFs may be also found in the electronic industry where miniaturization efforts for the nanoscale technology recommend the use of fluids with zero-surface-tension property that are SFs. SFs are indeed becoming more essential nowadays.

Another domain of interest of the present proposal concerns propulsion with application to the automotive and aerospace science and technology where SFs may be considered as propellants [2]. Indeed, many fluid mechanical devices involve thermodynamic phase transition from a subcritical to a supercritical state. As example, the high-pressure combustion chambers of rocket engines operate at pressures and temperatures well above the thermodynamic critical points of the injected propellants, *i.e.* in a *supercritical* state (see Fig. 1). Such engines operate at very high pressure, typically of the order of 10.0 MPa whereas the critical pressure of hydrogen and oxygen is respectively 1.3 MPa and 5.0 MPa.

A final example concerns the *clean coal combustion and technology of transformation*. Indeed, coal, the most abundant energy resource, will continue to be dominant in China's energy scheme for a very long time [3]. Therefore, sustainable development requires the development and deployment of clean coal technologies such as supercritical and ultra-supercritical boilers, circulating fluidized bed combustion, and integrated gasification combined cycles. Clean Coal Technologies (CCTs) are technologies which facilitate the use of coal in a viable economic and human environment. A basic idea for the CCTs is the development of efficient systems in order to decrease the amount of coal used to generate the same amount of power. Some CCTs have already seen commercial application in industrialized countries. Advanced electric power generation systems that generate electricity with greater efficiency and fewer environmental consequences are undergoing development in many countries.

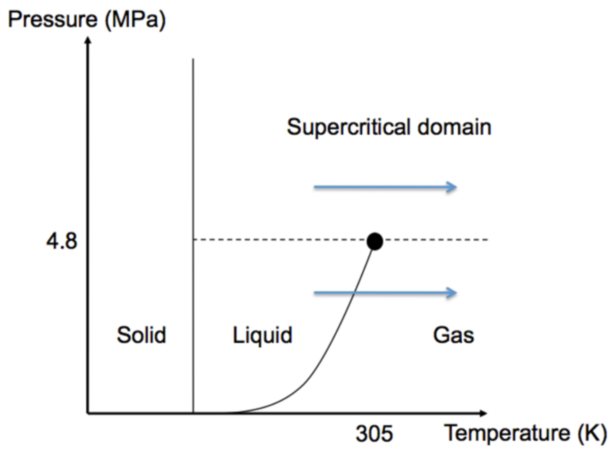

Figure 1: Pressure-Temperature diagram for ethane species.
Interest of the present study: arrows.

In particular, the pulverized coal combustion with supercritical steam cycles, together with flue gas cleaning units is under current research and development. However, units with subcritical boilers tend to have somewhat higher emissions of sulphur oxides (SOx) and nitroxides (NOx) per kWh than units with supercritical boilers. Indeed, subcritical systems are less efficient generating less kWh per unit of coal input. To improve the plant performance, the introduction of supercritical or ultra-supercritical steam conditions and the use of emission control devices is then necessary.

2. Objectives

Mixing is one of the most important phenomena in combustion devices because it determines combustion efficiency and stability along with heat transfer characteristics. In addition, most of the current understanding of turbulence and mixing is the result of atmospheric-pressure studies providing numerous numerical and experimental databases are available. A similar work has to be undertaken for sub-, trans- and super-critical flows investigation, *i.e.* real-gas effects have to be considered [4,5]. Indeed, this research field lacks of indisputable experimental data, useful for the numerical code validation. Simulation has made serious progress in the last decade but still need well-documented experimental test cases. Actually, only few experimental test-benches are able to reach/run supercritical cases. Three are located in the USA (Pennsylvania State Univ., Univ. of Florida and AFRL), two in Germany (M51 and P8 at DLR) and one in France at ONERA (Mascotte). Except facilities from Univ. of Florida [6], they are all running hot fire configurations dedicated to rocket issues that already are highly complex systems. In addition, no convincing experimental data are available. **The declared objective of REFINE is to fill out this need by the mean of simple well-defined experimentations with very advanced diagnostics to deliver the finest information. REFINE addresses then Basic Research.**

These investigations should provide a better understanding of atomization, mixing and flow dynamics for high-pressure subcritical and supercritical jets. It is expected that these studies will also lead to an enhancement of physical models, which will be used for achieving an improved design methodology. For this reason, cryogenic and supersonic flows are ruled out

since a substantial device and sensitive technology are required. Studying a fluid flow injection close to the critical point is beyond the objectives of REFINE as the conditions of injection may not be well controlled and the use of the proposed diagnostics not totally guaranteed.
The REFINE project will be confronted to serious challenges. The first one is the realization of a clean high-pressure experiment. Even if the CORIA lab has a great experience in high-pressure injection, it is always a challenge when extending the area of research. Secondly, the X-ray diagnostics setting-up, which is the project keystone, has to deliver a non-polluted density measurement and GREMI is perhaps the only French Lab able to realize this task. Among the potential candidates that can be used as a supercritical fluid, ethane (C_2H_6) is selected because its critical properties, Tc=32.18°C and Pc=4.8174 MPa, considerably simplify the experimental device setting-up used to produce well-controlled subcritical, transcritical and supercritical conditions; it is one of the simplest hydrocarbons so that the theory of its behavior is easier to establish; it is an hydrocarbon and hydrocarbons are used everywhere; finally, combined with Helium, it allows a great contrast for X-ray diagnostics, key point of the methodology. Once the X-ray diagnostics calibrated, other classical techniques (shadowgraphy, Schlieren, *etc*.) could be incorporated more easily for comparisons to the X-ray data. **The CORIA Lab has the objective to become the scientific reference for high-pressure systems by providing to the scientific community a comprehensive database.** This criterion will be pertinent to appreciate the success of REFINE. Finally, a first attempt has been performed very recently (see Fig. 2) leading to very promising results.

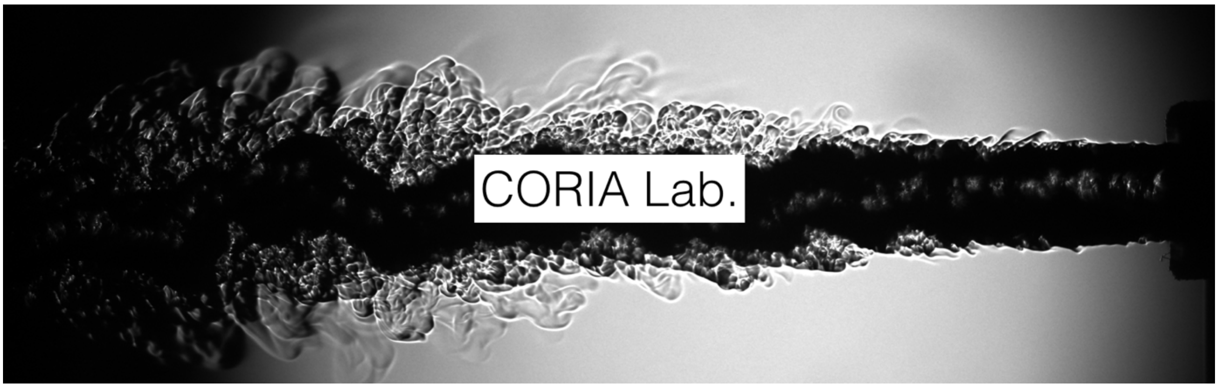

Figure 2: Injection of ethane into nitrogen at supercritical pressure.

Ph.D. Schedule:

Year 1: Test bench and injector design, preliminary tests and experimental program elaboration. Bibliography.

Year 2: Shadowgraph visualization setup and measurements. X-Ray setup then measurements on sub- trans- and supercritical conditions.

Year 3: Data analysis (shadowgraph images treatments, X-Ray images treatments), participation to scientific congress, dissertation writing.

3. Bibliography

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