The 8th International Supercritical CO_2 Power Cycles Symposium
February 27 – 29, 2024, San Antonio, Texas
Paper 13

Visualizing the turbulent heat transfer of horizontal sCO2 flows

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ABSTRACT

Supercritical energy conversion systems are viable candidates for the sustainable generation of power and heat. However, an inadequate understanding of the complex heat transfer phenomena at supercritical pressures hinders the reliable and efficient design of heat transfer equipment for these power systems. So far, numerous fundamental challenges in fluid mechanics and heat transfer have remained experimentally untouched for supercritical media. In this work, the results of a first set of optical experiments are introduced, aimed to explore the fundamental challenges at hand. More precisely, we investigate the influence of buoyancy on a turbulent flow of supercritical carbon dioxide in the stably stratified configuration using shadowgraphy. Here, a near-immediate and significant decrease in the turbulent intensity of the flow is perceived upon the addition of heat.

INTRODUCTION

In pursuit of more efficient and potentially sustainable energy conversion systems, new designs are developed to operate at increasingly extreme conditions, for instance in the thermodynamically complex region beyond a fluid's critical point. In the supercritical region, a clear distinction between the liquid- and gas phases ceases to exist. Instead, the boundary between the liquid- and gas-like phases is characterized by sharp but continuous gradients in thermodynamic properties. A near boiling-like transition in thermo-physical properties can be found when crossing from one pseudo-phase to another, entirely in the absence of a vapor-liquid interface. As such, supercritical fluids can display flow- and heat transfer behavior that deviates greatly from what is expected for ideal fluids, therewith greatly complicating the design and implementation of heat transfer equipment for novel supercritical energy conversion systems.
One of the main causes for this deviatory behavior can be highlighted using the flow problem described in figure 1. Here, a fully developed flow with a set Reynolds number in a differentially heated cavity is considered for air and water at atmospheric conditions, and for supercritical

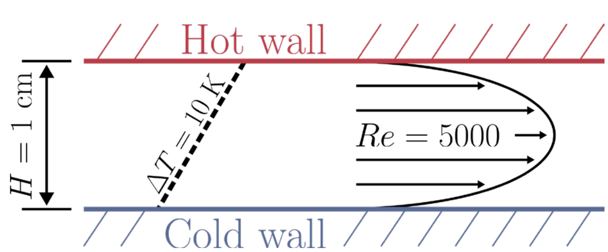


Figure 1: Fully developed flow in differentially heated cavity.

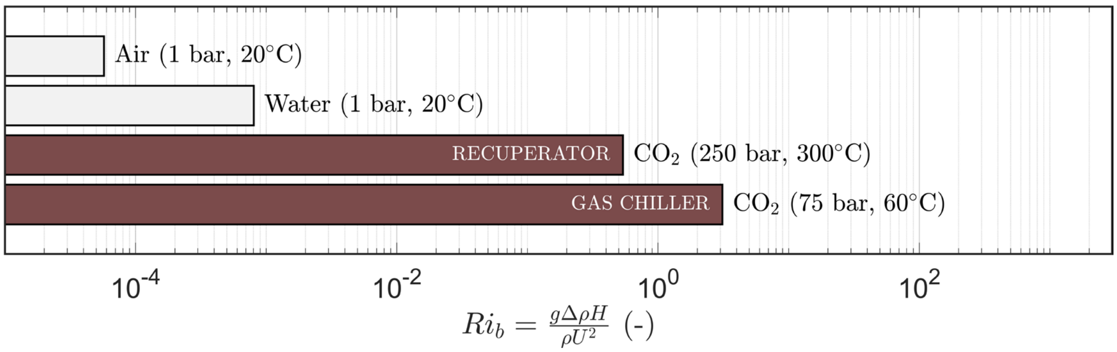


Figure 2: Comparison of $\boldsymbol{Ri}_{\mathrm{bulk}}$ between carbon dioxide at supercritical conditions, and air and water at atmospheric conditions (1 barA, 20°C), for the flow of figure 1.

carbon dioxide. In this setting, the Richardson number – a measure of the ratio of buoyant forces in comparison to inertial forces – of the supercritical medium exceeds the value found for the ideal substances by five orders of magnitude, as shown in figure 2. As such, flows of supercritical carbon dioxide are far more likely to be dominated by buoyancy than flows of ideal media at atmospheric conditions at similar flow- and heating rates. As a result, the performance of heat exchangers with supercritical fluids is often strongly influenced by the grave, local, near-wall expansion and acceleration or shrinkage and deceleration of fluid, dependent on the configuration and the direction of the heat transfer. Therewith, new and different heat transfer correlations are needed to accurately capture the heat transfer rates of supercritical media for various heat transfer arrangements. Whereas many new configuration-specific heat transfer correlations have emerged in open literature (Cabeza et al. 2017, Ehsan et al. 2018), the experimental data from which they are derived is often of considerable variance when buoyant contributions are no longer negligible (Bruch et al. 2009, Yoo 2013).

The aim of our work is to better understand how buoyancy modulates the turbulence and the turbulent heat transfer of supercritical media, by complementing existing heat transfer experiments with optical investigations capable of yielding two-dimensional data fields of various quantities at improved spatial resolutions. More precisely, we will present a first series of shadowgraphs of a continuous, horizontal flow of carbon dioxide that is heated in the top-down configuration. The shadowgraphs were obtained using our recently developed experimental facility, the *SCO₂PE*.

SETUP & METHODOLOGY

A high-pressure test section for optical experiments of flows of supercritical carbon dioxide lies at the core of the *SCO₂PE* facility. In the test section, bilateral optical access is provided to a rectangular channel with tempered borosilicate glass visors, shown in figure 3. Heat is added to the flow of supercritical carbon dioxide using a polyimide film heater (50x50 mm, max 40W) in the top-down configuration. The film heater is mounted on the back side of a 0.8 mm thick aluminum plate, intended to avoid local surface steps whilst maintaining a limited conductive resistance. The temperature of the heater-side wall is measured using two type-K thermocouples. As the test section of the *SCO₂PE* is modular, the flow geometry can be altered to study either developing or fully developed flows. For all results presented in this document, a developing channel flow is expected at the location of the optical slit. For this configuration, the supercritical medium is conditioned in a settling chamber that includes a honeycomb structure, a series of wire meshes and a contraction directly upstream of the rectangular channel.

Figure 3: Schematic of considered flow geometry. In the figure, supercritical carbon dioxide flows from left to right.

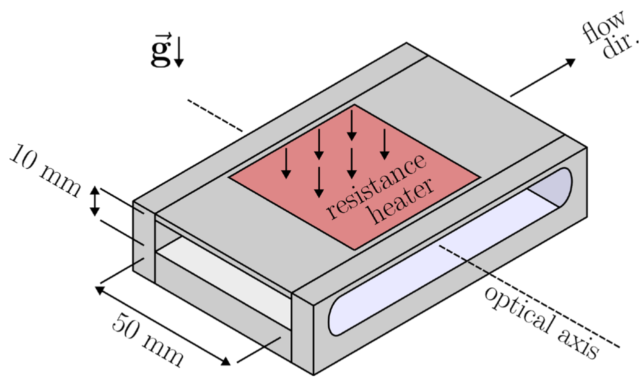
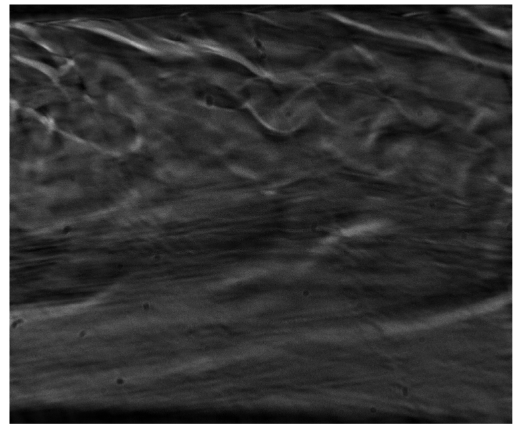


Figure 4: Instantaneous shadowgraph of CO_2 at $p_{\mathrm{bulk}} = 80.4$ bar, $T_{\mathrm{bulk}} = 29.2$°C, $\dot{m} = 5.8$ g/s, $Re_{\mathrm{bulk}} = 3000$, $\dot{q} = 0$ kW/m^2.



A steady, continuous flow is provided to the considered rectangular channel by placing the test section at the foot of a natural circulation loop (NCL). Here, the large gradients in density of the supercritical medium are exploited to naturally generate a flow rate of up to 0.15 kg/s, at up to 140 bar and 65°C (Draskic et al. 2023). As the fluid is circulated at low Mach numbers to the section, viscous heating is negligible and instead any non-ideal behavior is induced through the transfer of heat with the foil heater. A natural circulation configuration is chosen to avoid the need for pump lubricants which contaminate the operating medium, or for delicate rotary seals. Furthermore, the NCL allows for the careful and stable control of the thermodynamic state of the fluid at the test section inlet.

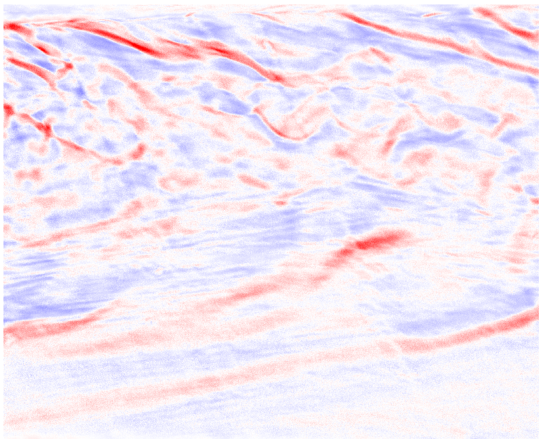
Shadowgraphy is used to yield insights into the non-ideal hydrodynamic behavior of the supercritical medium. The images are recorded using a Pixelink PL-D755MU-T (2448x2048 pixels, monochromatic, $\geq 20\mu$s exposure time) USB camera. To limit the blurring of the out-of-focus flow on the image plane (Ota et al. 2015), a collimated monochromatic LED is used. In shadowgraphy, variations in refractive index along the optical path make that a light source that is homogeneous in brightness forms an image that is of spatially variable intensity after having passed through the setup. As the image of a shadowgraph depends on the second path-integrated spatial derivative of the refractive index (Settles 2001), shadowgraphs are indicators of gradients in thermodynamic properties, rather than quantitative measures of the mean value of the refractive index. Therefore, an assessment of the perceived light intensity of the shadowgraph can give insight into the presence and evolution of thermal structures only when a flow is turbulent and compressible.

RESULTS AND DISCUSSION

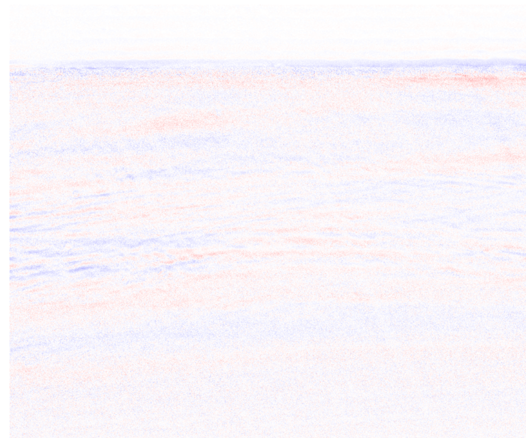
An instantaneous shadowgraph of an unheated flow of carbon dioxide is shown in figure 4. The present spatial image intensity variations indicate that the flow is inhomogeneous in refractive index, and therewith density. The image brightness furthermore fluctuates in time. As the flow is not locally heated, i.e. $\dot{q}$=0 kW/m^2, any inhomogeneity in the thermodynamic properties is generated upstream of the considered rectangular channel. The same shadowgraph is shown in figure 5a, however here the local image intensity is presented with respect to the reference brightness of a background image. Where the local intensity exceeds the background intensity,

Figure 5: Instantaneous shadowgraph intensity $\boldsymbol{I}$ with respect to the mean intensity value $\bar{\boldsymbol{I}}$. Increased brightness shown in red $(\boldsymbol{I}-\bar{\boldsymbol{I}})$, decreased brightness in blue $(\boldsymbol{I}_{\boldsymbol{max}}-(\boldsymbol{I}+\bar{\boldsymbol{I}}))$. Carbon dioxide at $\boldsymbol{p}_{\text{bulk}}=$ 80.4 bar, $\boldsymbol{T}_{\text{bulk}}=$ 29.2°C, $\dot{\boldsymbol{m}}=$ 5.8 g/s, $\boldsymbol{Re}_{\text{bulk}}=\mathbf{3000}$.

a) Unheated case, $\dot{\boldsymbol{q}}=\mathbf{0}\ \boldsymbol{kW/m^2},\ \boldsymbol{Ri_h}=\mathbf{0}$.



b) Top-heated case, $\dot{\boldsymbol{q}}=\mathbf{13}\ \boldsymbol{kW/m^2},\ \boldsymbol{Ri_h}=\mathbf{40}$.



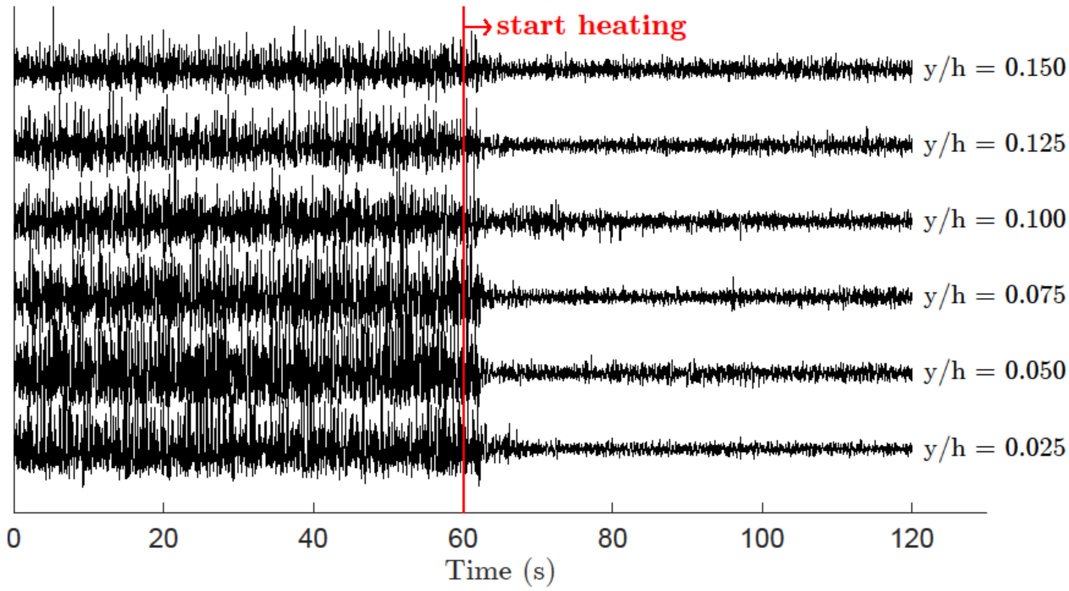
the shadowgraph is colored red with an increasing saturation for an increasing exceedance, whereas the opposite is true for the blue colored regions. Figure 5a indicates the presence of the boundaries of numerous thermal structures in the considered domain, at various orientations, sizes, and image intensities.

When the heating is in the direction of gravity, a lower density layer is formed on top of the denser bulk flow when the channel is heated, and a stably stratified flow emerges. In cases where the gradients in density are significant, the stable stratification of a flow can lead to a sharp decrease in turbulent intensity of an initially turbulent flow, and to the subsequent relaminarization of the flow (Peeters et al. 2016, Zonta and Soldati 2018). Figure 5b shows the relative brightness of an instantaneous shadowgraph for identical process conditions as for figures 4 and 5a after the induction of top-down heating, at a heat flux of $\dot{q}=13\ kW/m^2$. Here, the perceived thermal structures in the channel are no longer of varying orientation, but are largely oriented in the streamwise direction, and are of limited vertical height. Here, the once randomly oriented thermal structures appear to have been aligned along the imposed density gradient, limiting their vertical displacement.

Additionally, the magnitude of the intensity deviations with respect to the background image has decreased significantly with respect to the results shown in figure 5a. As shown in figure 6, this is not only true for the instantaneous result of figure 5b, but holds for any point in the considered domain. Here, a near-immediate decrease in intensity fluctuations is shown for an array of points close to the heated top-surface. The location of the considered point in figure 6 varies in time, as the image height h decreases after the heating is commenced because of a modulation of the mean density in the rectangular channel, as can be deducted by comparing figures 5a and 5b.

Despite being qualitative in nature, the methodology and results above can already help explain the unexpectedly low heat transfer rates in specific configurations of empirical heat transfer

Figure 6: Image intensity $(\boldsymbol{I}-\bar{\boldsymbol{I}})/\bar{\boldsymbol{I}}$ over time, for various vertical locations with increasing distance $\boldsymbol{y}$ from the top wall. Carbon dioxide at $\boldsymbol{p}_{\text{bulk}} = 80.4$ bar, $\boldsymbol{T}_{\text{bulk}} = 29.2$°C, $\dot{\boldsymbol{m}} = 5.8$ g/s, $\boldsymbol{Re}_{\text{bulk}} = \mathbf{3000}$. Top-down heating ($\dot{\boldsymbol{q}} = \mathbf{13}\ \boldsymbol{kW/m^2}$) is commenced after 60 seconds in the figure.



campaigns with supercritical media. In the shown case, the vertical migration of eddies and thermal structures close to the top wall is limited by the imposed density gradient of the stably stratified heating, limiting the turbulent intensity of the flow as a result. As such, the rate of heat removal is expected to decrease greatly with respect to an ideal fluid case in which vertical movement within the flow away from the wall is mostly unrestricted. However, for the findings to be general and of use for the development of heat exchangers for novel energy conversion systems, the current methodology needs to be extended to include quantitative local measurements of density or temperature. Only then, the problem can be accurately described and bounded using relevant dimensionless parameters.

CONCLUSIONS

A set of shadowgraphs is presented in this work, aimed at visualizing highly non-ideal, continuous flows of supercritical CO_2. Here, the shadowgraph of an initially turbulent, horizontal flow subjected to top-down heating has been shown to strongly reduce in image intensity variation, suggesting that a reduction in the turbulent intensity of the flow has taken place. The consequent expected decrease in heat transfer rate can greatly lessen the performance of heat transfer equipment with supercritical media, needed for the development of new, sustainable energy conversion cycles.

ACKNOWLEDGEMENTS

This work was funded by the European Research Council grant no. ERC-2019-CoG-864660, Critical.

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