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Experimental and numerical analysis of the convective flow induced over a dry-ice bank with Particle Image Velocimetry

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Abstract. The utilization of carbon dioxide in new technologies opens a wide range of interesting applications which depend strictly upon heat transfer phenomena. The momentum on the deployment of Carbon Capture Utilization and Storage (CCUS) infrastructures will potentially enlarge the diffusion of technologies for the utilization and recycling of CO₂. Such applications, however, require appropriate laboratory investigations for a complete characterization of the CO₂ thermo-fluid-dynamic behaviour. The safety management of carbon dioxide is important; thus, accurate modelling is needed since solidification and sublimation of dry-ice can be very challenging to predict analytically. One of the dry-ice applications is the utilisation in refrigeration cycles and in novel CO₂ heat pump technologies. For this reason, knowledge about the entity of sublimating CO₂ from a solid surface is crucial. This work proposes an innovative experimental setup for the measurement of temperature and convective velocity fields in the sublimating phenomenon of CO₂ under atmospheric conditions by means of Particle Image Velocimetry (PIV). The experimental results have been compared and validated with numeric CFD models.

1. Introduction

The capture, utilization and storage of carbon dioxide is considered as a game-changing technology in the new energy transition process. The path of valorisation and exploitation of natural resources to reduce their global footprint rely also on the capability to reuse the CO₂ as a product. The solid phase of CO₂ can form during the processes, and it has implications also on safety [1,2]. The understanding of heat and mass transfer during the sublimation of a dry-ice bank can be crucial for the safe operation of equipment such as heat pumps [3] and refrigeration [4,5]. Moreover, dry-ice can form during the transport of CO₂ in pipelines, its formation can impact the normal operation and increase the risk of ruptures [6,7]. Mazzoldi et al. [8] analysed the sublimation of dry-ice banks analytically and presented a model to evaluate the energy balance. The sublimation rate of a dry-ice bank has been investigated experimentally by Mocellin et al. [9], mass flowrate, temperature and fluxes have been also measured. Despite several literature works focused on the study of sublimation in terms of mass flowrate, there is no evidence of a direct measurement of air particle velocity induced by a sublimating dry-ice bank. In this work, an innovative setup has been realized for the experimental investigation of flow-induced velocity over a sublimating dry-ice bank with Particle Image Velocimetry (P.I.V.). The results have been also compared with a CFD model through the commercial code ANSYS Fluent.



2. Materials and methods

A novel test bench located at the Department of Industrial Engineering and Mathematical Sciences of Università Politecnica delle Marche (Italy) has been set up in order to measure velocity fields with 2-D Particle Image Velocimetry (P.I.V.) system. A unique innovative setup has been designed for the purpose of sublimation measurement of dry-ice and the convective flux induced by the process. Temperature has been monitored with T-type thermocouples during the entire sublimation process at different locations.

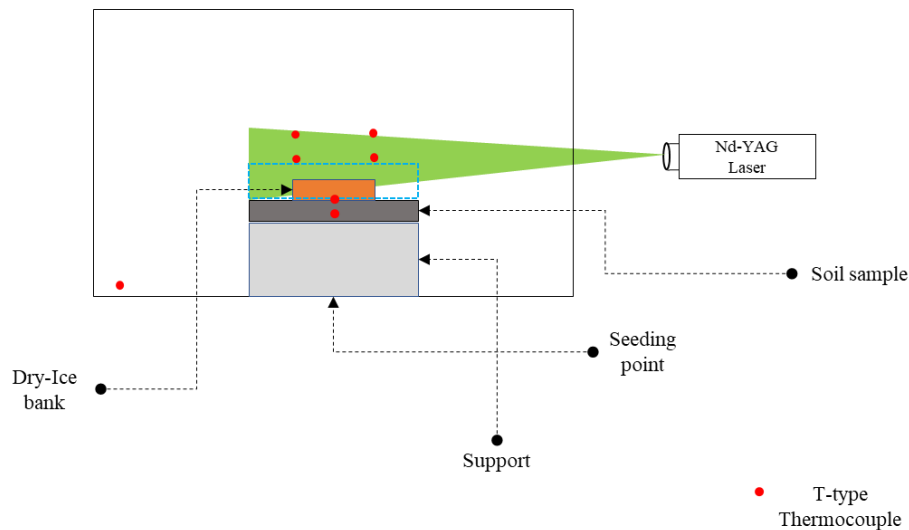


Figure 1 – Particle Image Velocimetry measurement setup

In Figure 1 the setup utilized has been schematized, and the dry-ice bank is represented in orange. The dry-ice bank sample dimensions were 0.15 x 0.105 x h 0.02 m with a total initial weight of approx. 0.4 kg. The sample has been placed over a box filled with soil (coarse-grained sand) to simulate a real terrain. The entire testing section was inside a transparent box to grant visual access of the phenomena and instruments. T-type thermocouples have been utilized for the temperature monitoring while the P.I.V. system has been utilized for the measurement of velocity over the dry-ice bank. The measurement setup was composed by several devices, including:

- FlowSense USB 2M-165 double-frame camera
- Dantec Dynamics® Continuous Laser
- Oil nebulizer device (Laskin type)
- Newport® Optical Pneumatic Table

The testing volume was included inside a casing with length of $L = 0.40$ m height $H = 0.47$ m and depth $D = 0.45$ m. The casing and the optic instruments were mounted on the Newport® optical table to ensure the maximum achievable stability and precision of the measure. To allow optic access to the camera and execute acquisition, the front wall was used, which was perpendicular to the CCD camera focus. The optical equipment, such as the CCD camera and the Laser, have been precisely positioned in relation to perpendicular axis directions from the test casing's front and side access, respectively. A Laskin-type oil nebulizer [10] connected to a compressed air line has been utilized with corn oil particles as a seeding medium.

3. Experimental campaign

The measurement of the velocity field has been performed over the dry-ice bank during the process of sublimation. P.I.V. has been utilized to visualize the particle motion and measure the seeding particle displacement. Alignment of the camera has been performed with respect to focus, distance, and elevation with free runs before the acquisition test. The P.I.V. system has been calibrated with a target, prior to the measurement campaign. The workflow procedure reported in Figure 2 has been followed during the measurement process.

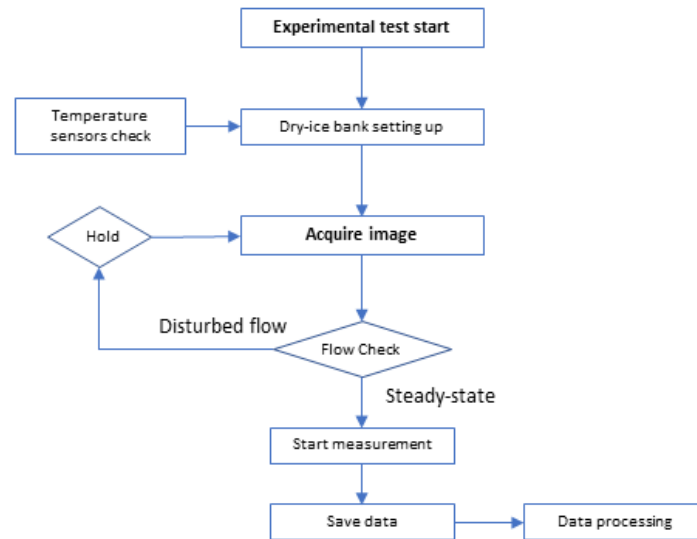


Figure 2 – P.I.V. measurement workflow

The velocity has been measured during the sublimation, however, in order to reduce the measurement system disturbances in the long process. Measurements have been conducted at different times from the beginning of the sublimation. In order to reach the steady-state of the flow, some seconds (around 30 s) were necessary to mitigate the effects of temperature equilibrium and the initial turbulence generated by the seeding injection at a higher pressure than the cavity one. The size of the images was 1920×1200 pixels with an interrogation area of 32×32 pixels. A total of 100 couples of images were acquired for every set-up test case. The time between images (Δt) on the double frame camera has been set within the range of 0.0083 s and 0.0125 s and adjusted based on the velocity magnitude induced by the sublimation. Images were masked outside the area above the dry-ice bank where the seeding was injected.

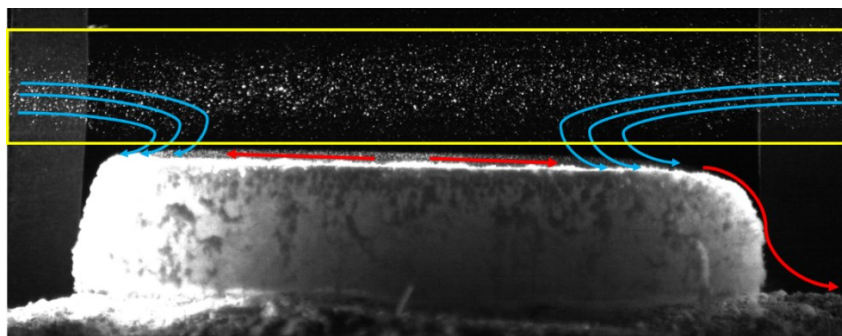


Figure 3 – Visualization of the airflow with the P.I.V.

Signals have been processed through Dantec[®] Dynamic Studio by using the proprietary adaptive cross-correlation algorithm, and a moving-average validation method to reject or accept vectors obtained with the previous algorithm. A 50% overlap of the areas was used both in horizontal and vertical directions [11]. The dry-ice bank due to sublimation reduced its dimension along the process, therefore since the mass is related to the heat transfer phenomena, the velocity showed a gradual decrease in magnitude. However, since the process is quite slow, in the order of $160\text{-}240 \text{ g/min} \cdot \text{m}^2$ [9], the measurement of the velocity was not impacted and a *de facto* steady-state case has been established. The maximum velocity achieved during the sublimation was registered at the beginning with a value of 0.017 m/s and two main vortexes have been observed. The duration of the entire sublimation process of the test was approximately 7 hours (25200 s). In Figure 3 a schematization of the visualized flow induced by the sublimation of the dry-ice bank has been superimposed on a P.I.V. measurement frame; the measurement area is represented with a yellow box. In the figure it is clearly visible the seeding particles utilized for the measurement as well as the dry-ice bank; the blue lines represent the measured flow while the red lines represent the flow of the sublimating CO_2 that was visible but not measurable with the utilized setup since the seeding and the laser has been focused to measure the flow above the dry-ice bank.

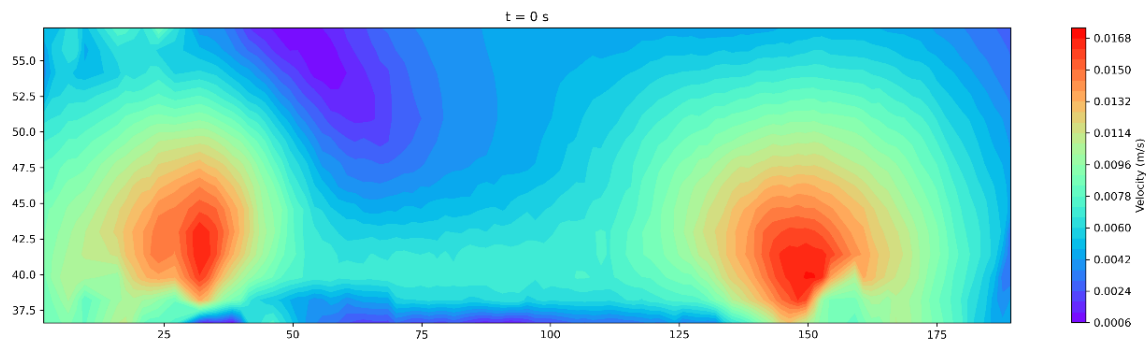


Figure 4 – Velocity magnitude measured with the P.I.V.

The processed data has been presented in Figure 4 in terms of velocity magnitude. Indeed, the particle displacement during the measurement has been paired with the calibration information and the velocity vector resultant has been reported. The maximum velocity has been registered in the proximity of the dry-ice lateral edge and a symmetric behaviour can be visualized for the airflow motion as schematized in Figure 3.

4. Numerical model and validation

The accurate prediction of the velocity flow induced by the sublimation of a dry-ice bank is dependent on the model utilized. The validation of computational fluid dynamic (CFD) models with P.I.V. is often proposed as a reliable method for forced and natural convection flows [12,13]. For this purpose, a comparison of a numerical model with the experimental data provided in this work is presented in this section. The model to simulate the phenomenon has been defined in the Ansys Fluent environment, and several models have been tested in order to achieve better convergence of the solution. The dry-ice bank edges have been extrapolated from Figure 3 with external software and fitted with a polynomial Spline in Rhinoceros 7. In this way, a better description of the nearby convection flows is achieved. A 2-D non-uniform structured mesh with $5.07 \cdot 10^5$ quadrilateral elements was developed with Fluent Meshing to describe the geometry of the solids and the air. A pressure-based transient simulation has been developed with the SIMPLE velocity coupling scheme, the applied convergence criteria were 10^{-6} for the continuity and momentum equations while 10^{-12} for the energy equation. The thermal boundaries of the domain have been defined as ambient temperature (295 K) at $t = 0 \text{ s}$ while the internal temperature of the CO_2 bank has been set to the measured value of 209 K. The final temperatures of the air as well as the soil have been then coupled and calculated by the model.

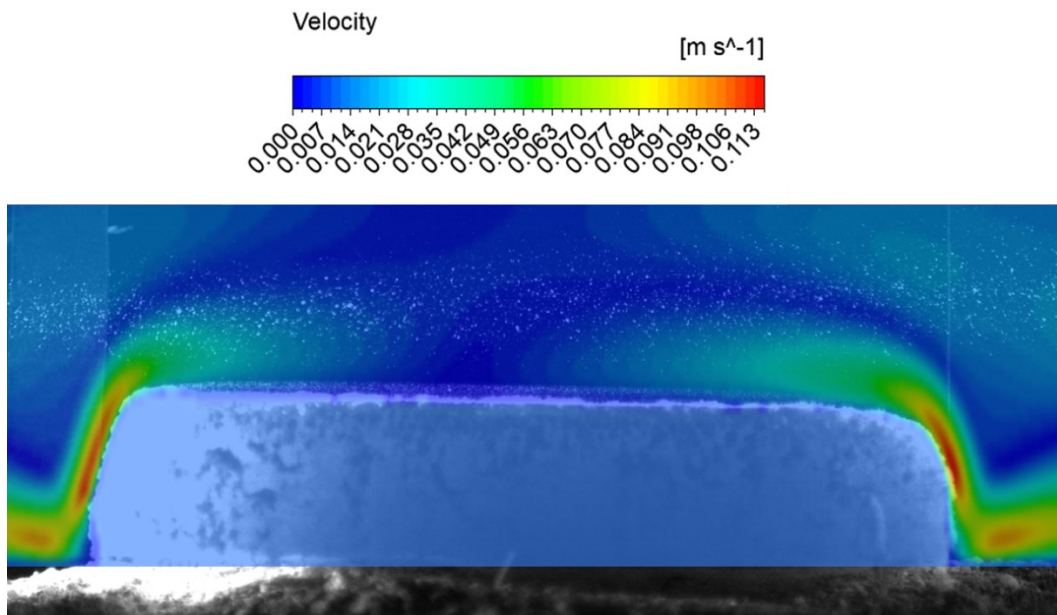


Figure 5 – Velocity magnitude numerical results from the CFD model

The airflow velocity calculated in the simulation is reported in Figure 5 in terms of velocity magnitude. The visible image of the dry-ice bank has been also superimposed on the velocity map in order to ease the visualization of the results. The induced flow above the bank has been calculated in the range from 0.00 to 0.07 m/s and is dependent on the position considered. A lower velocity zone is shown as expected in the central part of the bank, this has been also validated from the measurements (see Figure 4). The maximum velocity predicted by the numerical simulation is around 0.113 m/s and it is located next to the lateral faces of the bank.

5. Conclusions

In this work, an experimental campaign for the measurement of dry-ice sublimation process has been presented. The velocity field induced by the sublimation process and the low temperature has been measured accurately with 2-D Particle Image Velocimetry technique. According to the results, a maximum velocity of 0.017 m/s has been registered in the first minutes when the temperature of the dry-ice bank was around -64°C . The numerical simulation showed a coherent velocity map if compared with the experimental observations. However, it should be noted that not all the velocity field has been captured with the P.I.V. in this experiment. In particular, the left and right sides of the dry-ice bank have not been included in the measurement at this stage. Despite that, a good agreement with the observation has been noted, while the velocity predicted by the simulation was slightly overestimated. Finally, this work poses a first look at the possibilities of the application of the P.I.V. system for the measurement of airflow of natural sublimating or evaporating substances. The measurements have been developed safely and successfully in a small-scale laboratory, opening the way to several opportunities in the field of P.I.V. measurements applied to liquid-gas or solid-gas phenomena.

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