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Velocity measurements of a bench scale buoyant plume applying particle image velocimetry

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ABSTRACT

This paper presents the experimental investigation of the buoyant plume above an electrically heated block of copper. The velocity field in a vertical plane along the plume axis is investigated via particle image velocimetry. Experiments with electrical power from 30 W to 96 W are carried out, which lead to heat source temperatures of 149–307 °C. The resulting flow is laminar for the lowest power setting and undergoes a transition to turbulent flow for higher heat inputs. With increasing heat input the point of transition from laminar to turbulent flow occurs at lower heights.

Time-averaged velocity fields are presented together with the according measurement uncertainty that results from the evaluation with particle image velocimetry. Based on these velocity fields a number of characteristic values for the plume is derived in different heights, e.g. maximum velocities, plume widths and flow integrals. In order to further evaluate the transition from laminar to turbulent flow the vertical velocity and the standard deviation of the horizontal velocity along the plume axis and as a function of the Grashof number are investigated. The transition occurs at Grashof numbers in the range $4 \times 10^8 < Gr < 2 \times 10^9$, which is in accordance with previous findings. In addition to the velocity measurements, the temperature stratification inside the enclosure is measured to quantify the ambient conditions.

1. Introduction

The understanding of thermal plumes is of importance for the applications in thermal engineering, like heating of buildings, but also in safety engineering, e.g. hot gas plumes above a fire. Experiments that study the thermal plume above a heat source were conducted by many authors. The aims range form the investigation of free plumes [1–4], to the thermal interaction of plumes with objects, like plumes [5] confined between vertical plates. Furthermore, within the last decades different non intrusive measurement techniques have been applied for the investigation of the flow field as well as the concentration field of buoyancy driven plumes [6–8].

The non intrusive measurement technique particle image velocimetry (PIV) has been developed about 30 years ago and has been used for numerous experimental studies since then [9]. The measurement principle is based on seeding the investigated fluid with tracer particles and subsequently deriving the flow velocity from particle images taken at a defined time interval. It is a well understood measurement technique, which is superior to many other methods because the investigated flow remains undisturbed and the obtained values are almost instantaneous. Flow velocities can be measured with high accuracy not only at a single location but in an entire plane or volume. These features make PIV the method of choice for the validation of many computational fluid dynamics (CFD) codes.

However, in the context of fire experiments, PIV is not yet widely applied for the validation of fire related CFD codes. To the authors knowledge, only a few PIV-based studies have been tailor-made for the validation of popular fire simulation tools such as the Fire Dynamics Simulator (FDS) [10]. Exemplary studies are [11–17]. There are manifold reasons for this, one may be the difficulty to apply PIV in real-scale experiments that include pyrolysis and combustion at high temperatures. For this reason the experiments described here are set up in small-scale and use an electrically heated block of copper as a heat source. Many of the above cited experiments are ultimately meant to be used for the validation of FDS and other CFD codes in typical fire safety scenarios. However, as a first step this paper only covers the experimental investigation of the undisturbed buoyant plume above the heat source.

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In the first section, the experimental setup and methods are described. In the following sections the experimental results are discussed. This includes estimates of the measurement uncertainty and an evaluation of the experiments' repeatability with regard to ambient conditions. For a quantitative comparison of the experimental results various characteristic values are derived, e.g. maximum velocities, plume widths and flow integrals. For a closer investigation of the transition from laminar to turbulent flow the vertical velocity and the scattering of the horizontal velocity along the plume axis as a function of the Grashof number are analyzed.

2. Experimental setup and methods

In these experiments the focus lies on the undisturbed buoyant plume that develops above an electrically heated block of copper. In order to confine the particles and to guarantee defined boundary conditions, the heat source is placed inside an enclosure. The air adjacent to the copper block is heated and rises due to its positive buoyancy, there is no forced convection involved. In the course of the experiments a temperature stratification develops due to the buoyancy of the warm air. The PIV measurements are carried out when steady state is reached and the temperature stratification does not change anymore. In this case, the same amount of heat which is brought in by the heat source is lost through the outer enclosure walls and ceiling. They function as a heat sink for the gas volume inside the enclosure. PIV is used to investigate the flow velocities within the plume for four different power settings. Additionally to the flow velocities, gas temperatures are measured at various positions in order to quantify the boundary conditions of the experiments.

A sketch of the experiment is shown in Fig. 1, a detailed description of the experimental setup and the applied methods follows. The chosen coordinate system has its origin at the center of the top side of the copper block and the z-direction indicates the upward direction.

2.1. Experimental geometry

The enclosure used for the particle confinement is made of polymethyl methacrylate (PMMA) and is 735 mm wide, 575 mm deep, and 650 mm high (inner dimensions). The PMMA slabs for the walls and ceiling of the enclosure are 5 mm thick, for the base plate a 12 mm thick board of plywood is used. Two holes in the base plate are used as particle inlet and exhaust respectively. A closable opening on the left side of the enclosure allows access after the instrumentation is set up. The enclosure as well as all the optical equipment are set up on an optical table, or, wherever this is not possible, rigidly connected to it. In this way any unwanted movement of components and equipment is prevented. The entire setup including the enclosure, the optical table, cameras, lasers and other equipment are inside a laser safety box, which is 3.0 m long, 2.0 m wide and 2.1 m high. This safety box is required to protect experimenters and bystanders from the Dual-Nd:YAG Laser, which is classified as class 4 laser. It is marketed by *InnoLas* under the tradename *SpitLight PIV Compact 400* and has a maximum repetition rate of 2×10 Hz, a beam diameter of 6 mm, a pulse width of 4 ns to 6 ns, and a pulse energy of $>2 \times 180$ mJ (both at 532 nm) [18].

Inside the laser safety box the temperature of the ambient air is measured in order to have realistic back wall conditions for the later simulations. Platinum resistance thermometers (Pt100) are positioned on either side of the enclosure with a few centimeters distance to the enclosure walls (T_6 and T_7). Compared to thermocouples they provide more precise and stable results. Because the investigated gas temperatures are moderate and steady, the higher temperature resistance and shorter response times of thermocouples are not relevant here. Inside the compartment the temperature stratification is measured. For this purpose five Pt100 devices (T_1 to T_5) are placed above each other in one corner of the enclosure; the distance to both adjacent walls is 100 mm. The uppermost device is placed with 60 mm vertical distance to the ceiling, the other devices line up underneath with a vertical distance of 120 mm to each other. Hence the undermost device is positioned 110 mm above the base plate. The devices are brought into the enclosure parallel to the expected thermal stratification, i.e. along the isotherms. In combination with the low temperature difference between inside and outside the enclosure the measurement error due to heat flux to the exterior is expected to be very low.

For constructing the heat source, a heating coil and a thermocouple are embedded inside the block of copper, see the technical drawing in Fig. 2. It is designed with a 10 mm grid in mind, which is advantageous for recreating the setup in CFD models with cartesian grids. In this way the geometry can be represented without

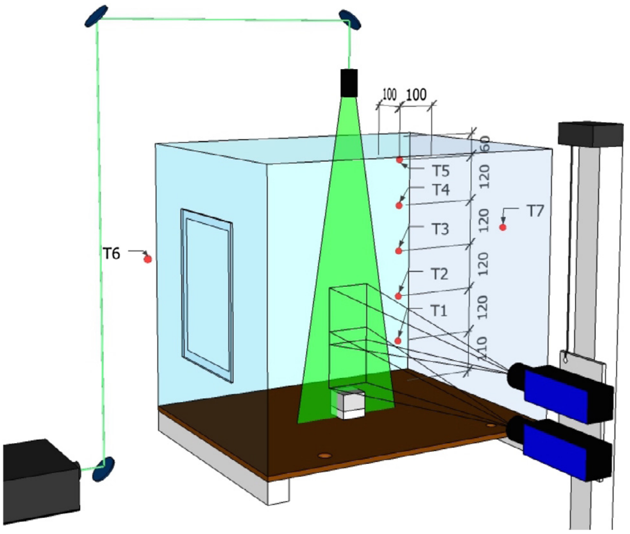

Fig. 1. Experimental geometry. The heat source is placed in the middle of an enclosure, which is required to confine the tracer particles. Temperatures are measured at various positions inside and outside the enclosure (T_1 to T_7). The laser light sheet illuminates a vertical plane along the plume axis. Both cameras can be driven upwards in order to capture the entire plume. Dimensions are given in mm.

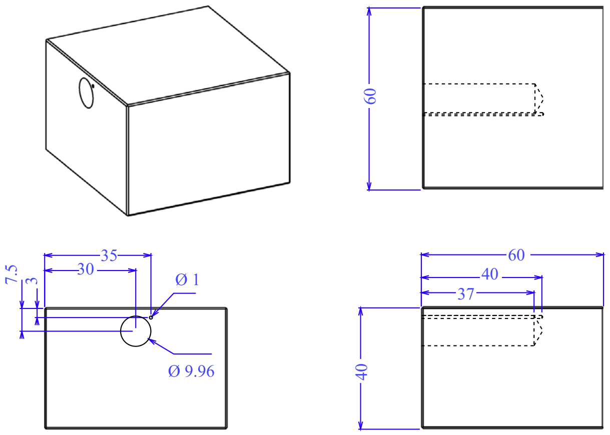

Fig. 2. For constructing the heat source, an electrical heating coil and a thermocouple are embedded in a rectangular block of copper with dimensions of 60 mm × 60 mm × 40 mm. All lengths and diameters are given in mm.