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Publication date:
2019

Document Version
Publisher's PDF, also known as Version of record

DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

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ISSN 1901-726X
DCE Technical Report No 287

Aalborg University
Department of Civil Engineering
Architectural Engineering

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December 2019

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Published 2019 by
Aalborg University
Department of Civil Engineering
Thomas Manns Vej 23
DK-9220 Aalborg Ø, Denmark

Printed in Aalborg at Aalborg University

ISSN 1901-726X
DCE Technical Report No. 287

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1. Foreword

The aim of this technical report is to provide detailed information about the two Double Skin Façade (DSF) full-scale test facilities that are used for experimental investigations at the Department of the Built Environment of Aalborg University, namely the "DSF Flow Channel" and the "DSF 23".

Double Skin Façades present various complex thermodynamic effects that make them very hard to study and model numerically. The complicated transient flow patterns and other phenomena taking place inside the Double Skin Façade cavities (see *Figure 1*) are very sensitive to the size of the latter and its boundary conditions. Consequently, there is currently no solid scientific consensus and agreement regarding how to model DSF systems with Computational Fluid Dynamics (CFD) models.

In that context, full-scale experimental studies are of very high relevance. Real flow patterns measured with Particle Image Velocimetry (PIV), flow velocity measurements with Laser Doppler, and precise temperature measurements on full-scale DSF setups with laboratory-controlled boundary conditions (DSF Flow Channel) as well as full-scale measurements in semi-exposed boundary conditions (DSF 23) are very useful to select, calibrate and validate numerical models.

All the necessary setup details and lessons learned from previous investigations are presented in this technical report so that one can readily recreate the described experimental facilities, improve them, and successfully conduct measurements.

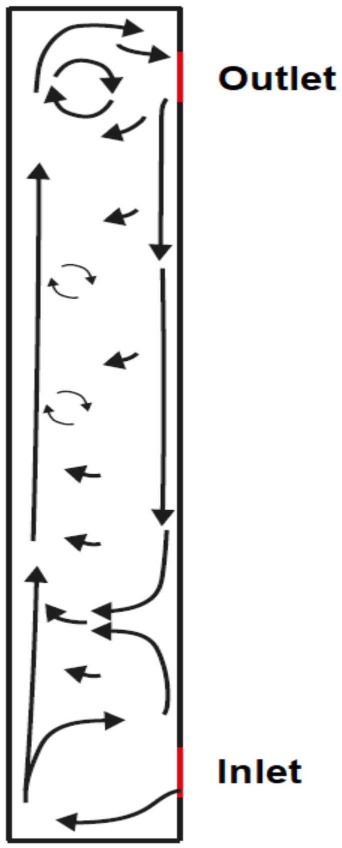

Figure 1: *Simplified side view of the airflow inside the DSF Flow Channel setup during experiments.*

2. DSF Flow Channel

2.1. Setup Description

The DSF Flow Channel is a vertical DSF experimental setup with a cubical ventilated cavity of internal dimensions **305 cm high**, **118 cm wide** and **40 cm deep**. The DSF Flow Channel setup is entirely located inside the indoor environment of a laboratory. It is thus possible to control precisely all boundary conditions of the ventilated cavity.

In addition, the DSF Flow Channel can be placed in a dark room to safely perform PIV or Laser Doppler measurements. PIV and Laser Doppler employ powerful lasers which can be harmful. It is thus very important to restrict the access to the dark room and block all possible line of sight into the dark room while the PIV and Laser Doppler tests are being conducted.

***Figure 2:** (Left) view of the full-scale experimental setup DSF Flow Channel without equipment or ventilation system mounted on it. The metal frames attached to the setup enable to place the PIV and Laser Doppler systems at any desired location in order to perform measurements in the entire volume of the ventilated cavity. (Right) illustration of top and front of the experimental set-up, including dimensions and Laser Doppler System position.*

PIV measurement is a non-intrusive velocity field measurement method that combines a powerful laser synchronized with the high-speed camera. The laser is positioned perpendicular to the camera and illuminates slices of the volume inside the cavity in a single plane normal to the sight of the camera (see *Figure 4*). The camera takes multiple successive pictures of the cavity while the laser illuminates the seeding smoke particles (smoke particles) in the cavity. The seeding particle movement and thus the velocity field of the air inside the cavity are then calculated by comparing the positions of the illuminated particles in between each successive image. The velocity vector analysis of the flow field is performed by dedicated software on a powerful computer. The PIV measurement is done on a rectangular volume slice (plane) with dimensions 16.5 x 16.5 cm. For each measurement slice, between 200 and 400 pictures are taken, with a time-step of 0.1 seconds between each picture.

To enable PIV and Laser Doppler measurement inside the DSF cavity, the front and sidewalls of the cavity are made of clear transparent plexiglass. The camera or the laser can be placed at the front or at the sidewalls in order to perform measurements in both horizontal directions. The metal frames attached to the setup enable to place the PIV and Laser Doppler systems at any desired location in order to perform measurements in the entire volume of the ventilated cavity. *Figure 2* (right) includes an illustration of possible position for Laser Doppler System. The laser position can be varied both vertically and horizontally (YZ -directions).

The values presented in the *Figure 2* (right) are the internal dimensions of the cavity. The aspect ratio of the cavity can be calculated as height over depth (H/b) resulting in ratio of 7.61. The inlet and outlet openings are situated on the bottom and top respectively.

Cross-section of the experimental setup (Figure 3) illustrates glass position, which is single piece plexiglass. The aluminum framing on the glass surface is attached from the outside, serving a support function only. The plexiglass is insulated from the aluminium framing with a thin layer of EPS.

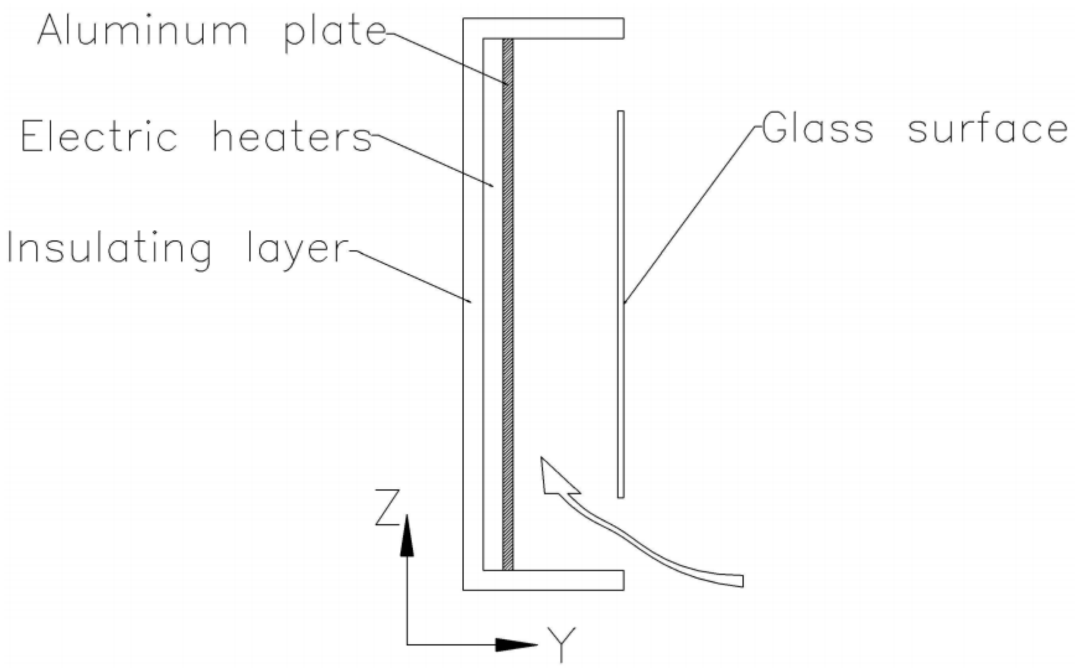

Figure 3: *Cross-section of the experimental setup.*

The seeding particles (smoke) must be supplied at a constant flow together with the inlet air supply to the ventilated cavity. This is ensured by the smoke buffer cabinet (see *Figure 4*).

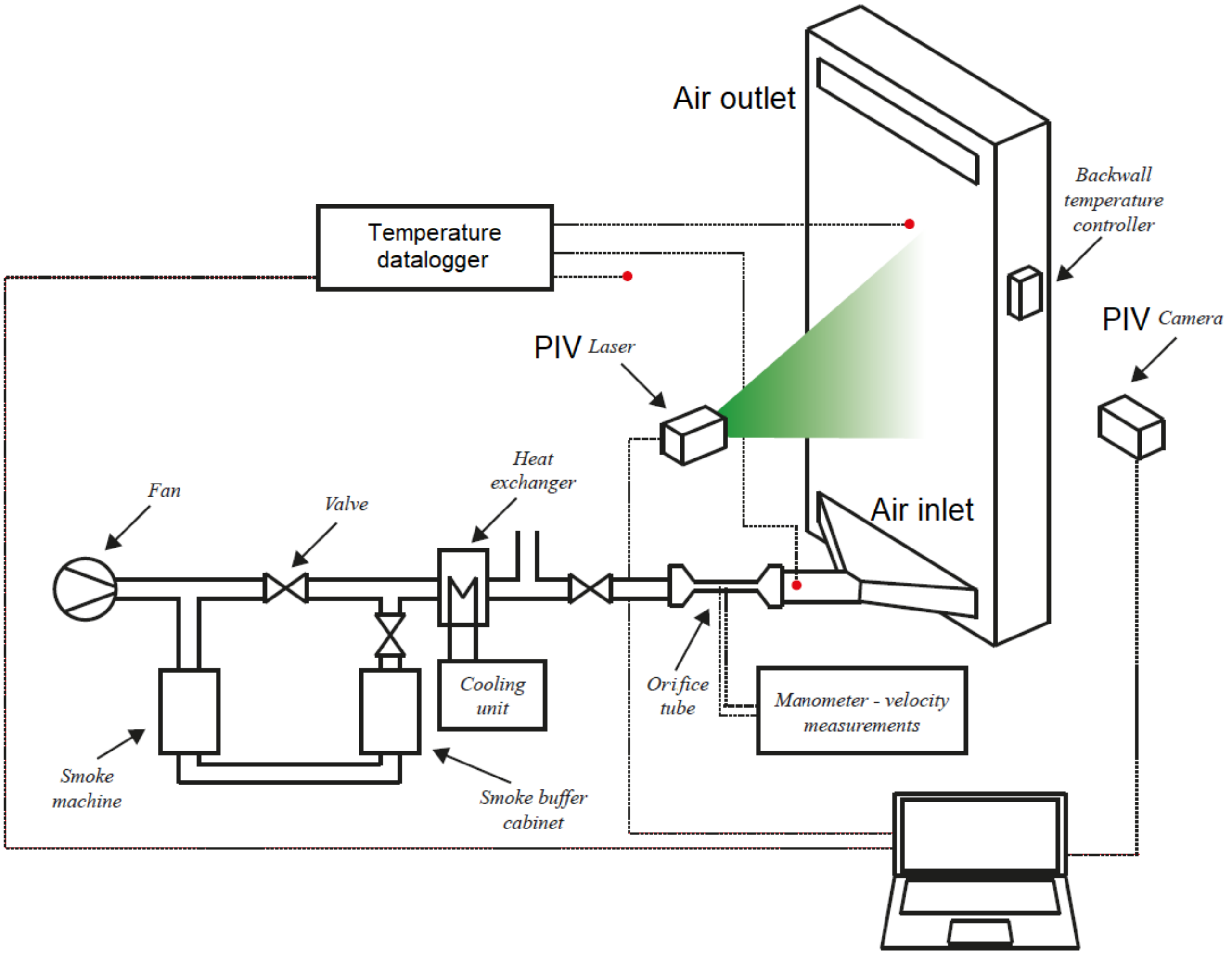

Figure 4: *Experimental setup for the PIV measurement of the airflow field inside the cavity of the DSF Flow Channel.*

The front and sidewalls of the DSF cavity are facing the laboratory environment which is kept at a constant temperature of 22 °C. The back wall is opaque and painted black. The back wall has an integrated controlled heating system (*Figure 3*) enabling it to maintain its internal surface facing the cavity at a constant temperature above the temperature of the laboratory.

The airflow rate and air temperature entering the cavity by inlet opening at the bottom of the cavity are maintained constant and can be adjusted by a controlled cooling heat exchanger and a variable speed fan (see *Figure 5* and *Figure 6*). The regulation is performed by a PI controller. The airflow rate is measured by an orifice place and a manometer. The temperature is measured by thermoresistors Pt100 placed at the inlet of the cavity.

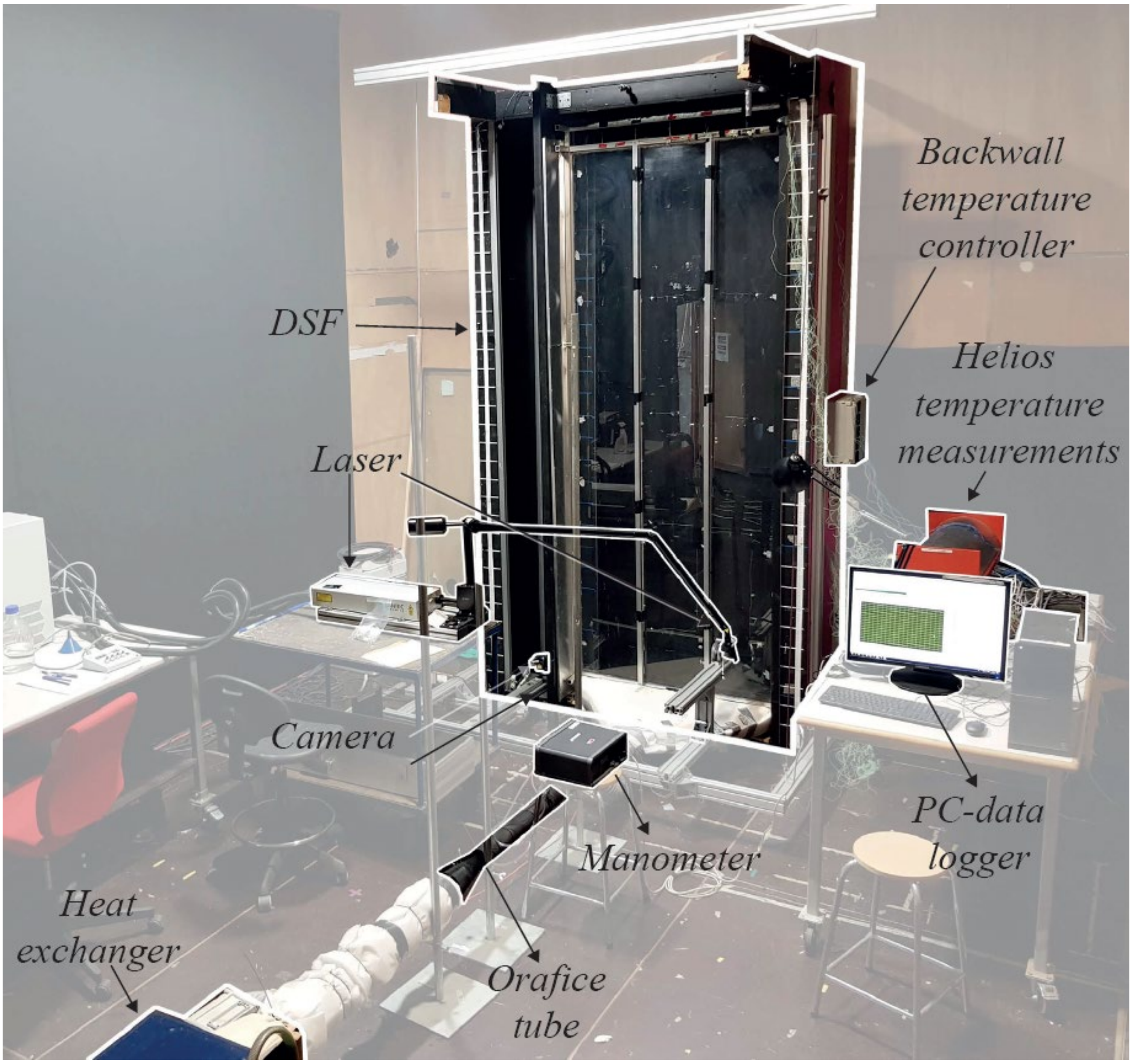

Figure 5: *Complete experimental setup for PIV measurement of the airflow field inside the DSF cavity, together with temperature measurements inside the cavity.*

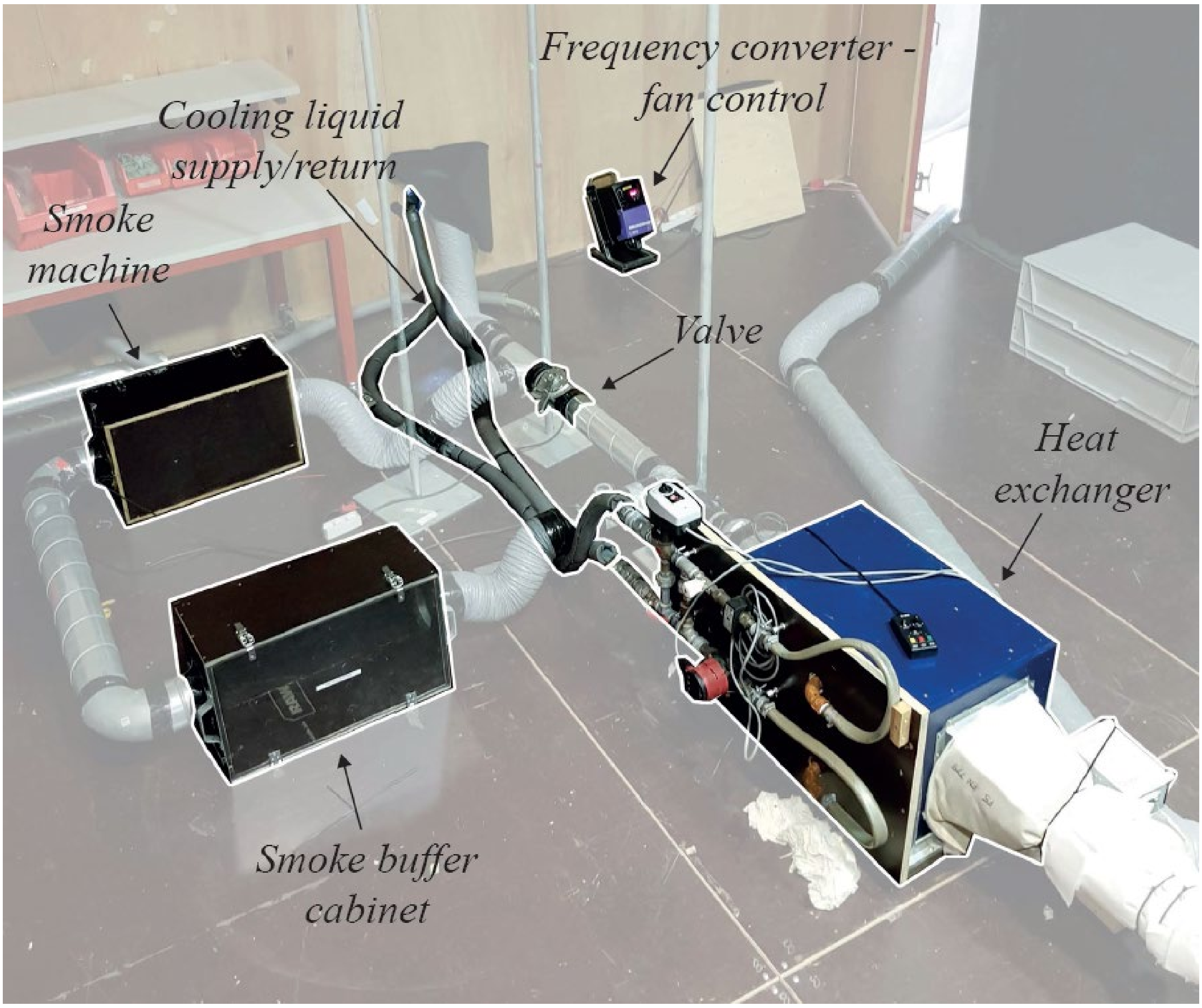

Figure 6: *Airflow rate regulation system, temperature regulation system and seeding particle production (smoke) for the air inlet of the DSF cavity.*

The temperature measurements at the inlet airflow, outlet airflow, and surfaces inside of the DSF cavity are performed with thin type-K thermocouples. The multiple thermocouples inside the cavity enable a good mapping of the temperature field on the surfaces of the cavity (see *Figure 7* and *Figure 8*) and the measurement of the temperature gradient at the center-line of the airflow in the cavity (see *Figure 9*).

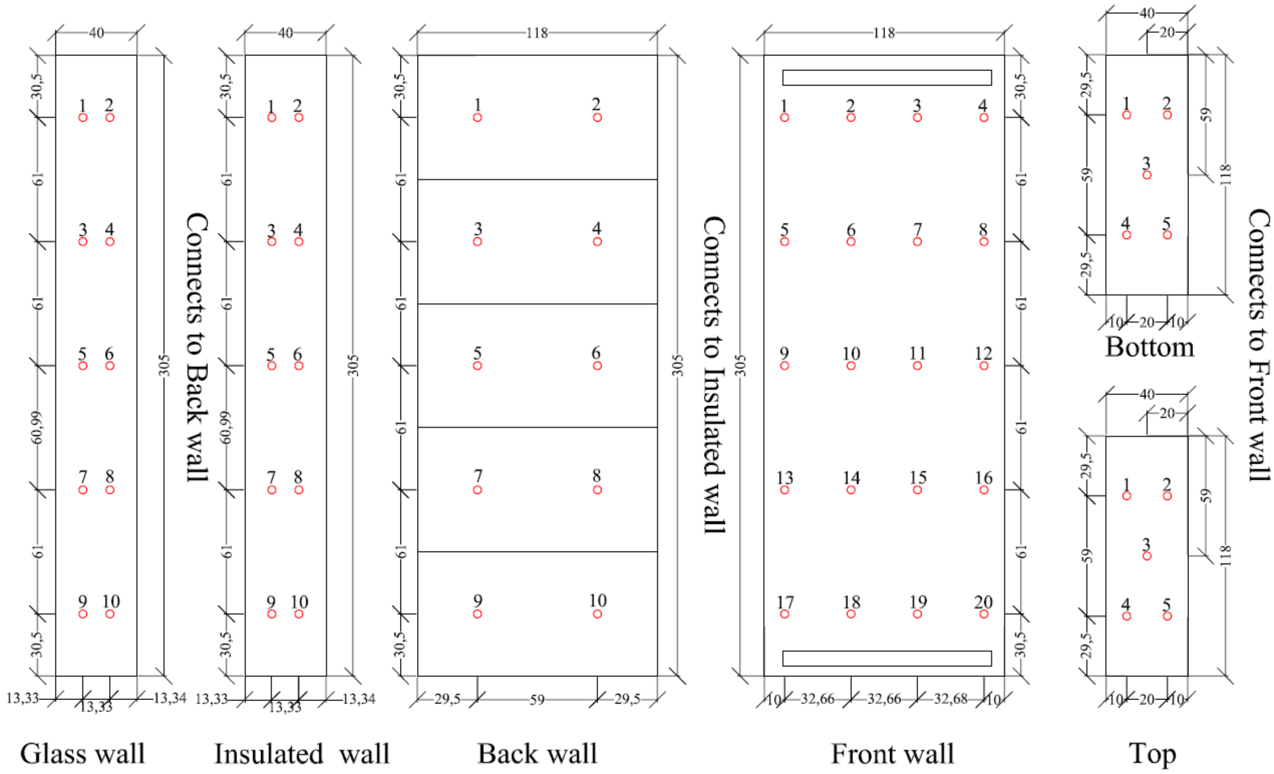

Figure 7: *Placement of the thermocouples inside the DSF cavity for the measurement of the temperature field (distances are indicated in cm).*

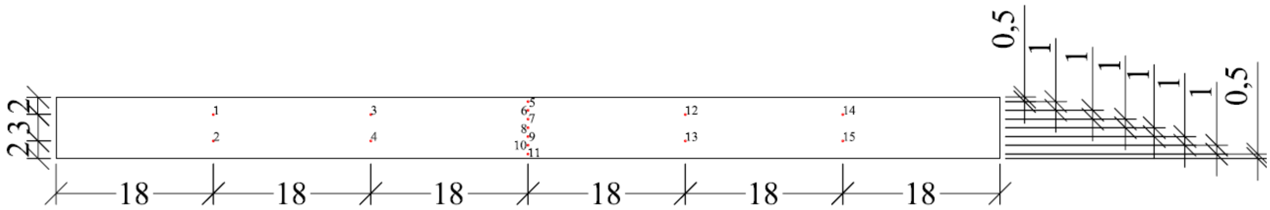

Figure 8: *Placement of the thermocouples at the outlet of the DSF cavity for the measurement of the temperature field (distances are indicated in cm).*

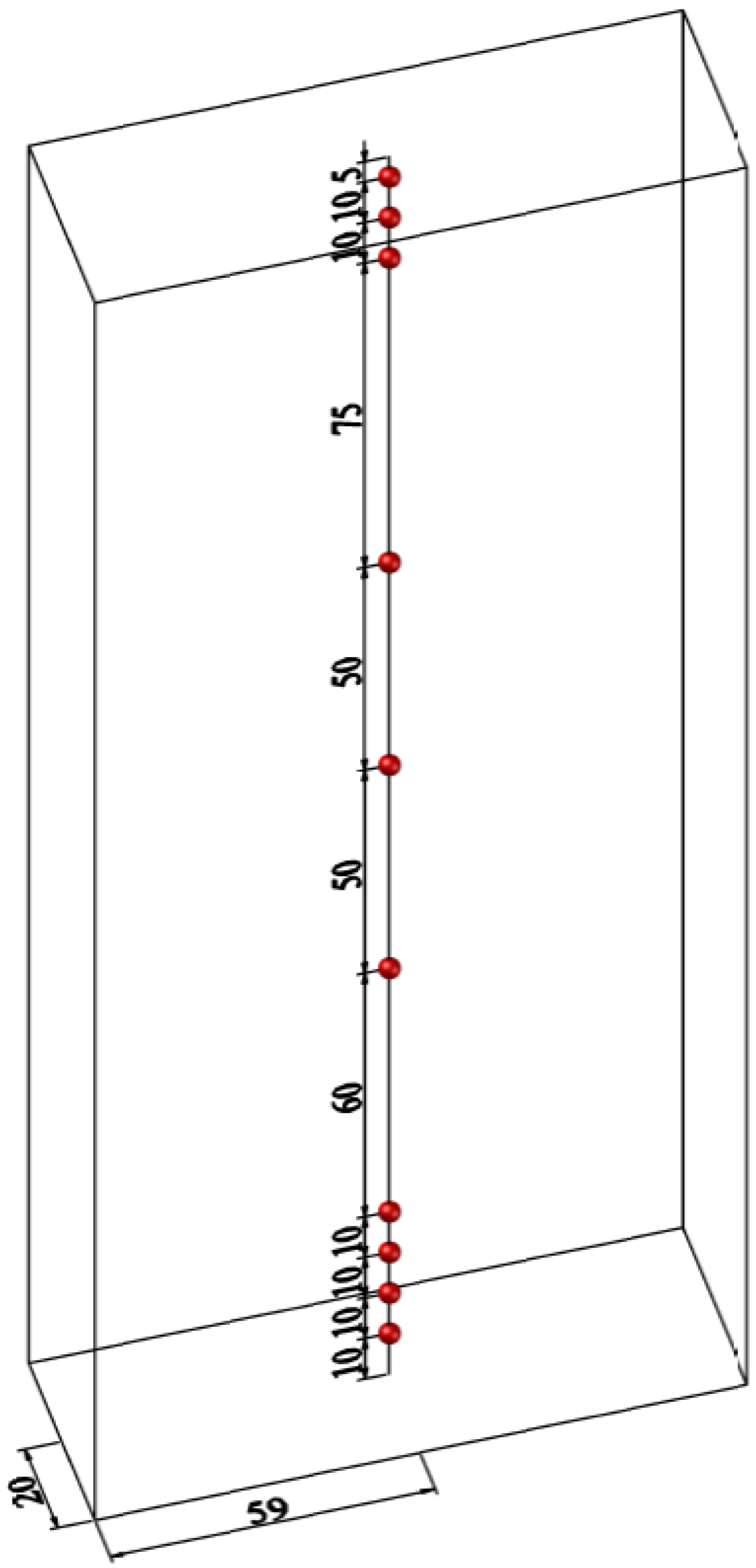

Figure 9: *Placement of the thermocouples at the center vertical line of the DSF cavity (distances are indicated in cm).*

2.2. Examples of Results from Experimental Investigations on the DSF Flow Channel Setup

Experimental investigations conducted on the DSF Flow Channel setup typically produce a detailed mapping of the airflow patterns and temperature distribution inside the DSF cavity. The latest investigations on the DSF Flow Channel showed the possible occurrence of a backflow located at the outlet of the cavity, and the presence of a stagnation point within the cavity. One can see in the figures below some examples of the measurement results produced from those experimental investigations. These examples do not include information about the experimental boundary conditions, as they are only meant to illustrate the potential of the experimental setup to answer multiple research questions related to flow dynamics of the double-skin façade.

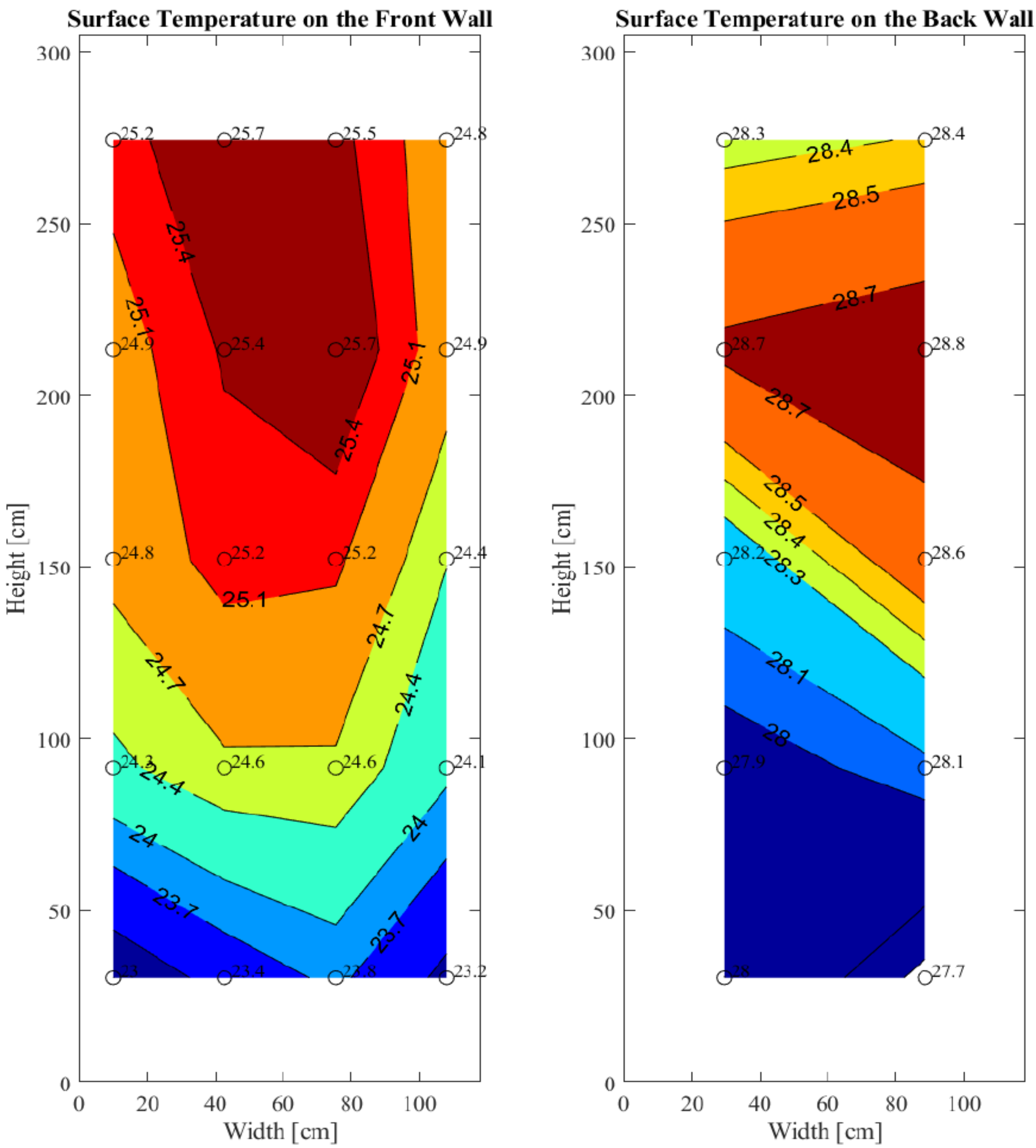

Figure 10: *Surface temperature distribution in the cavity of the DSF Flow Channel setup.*

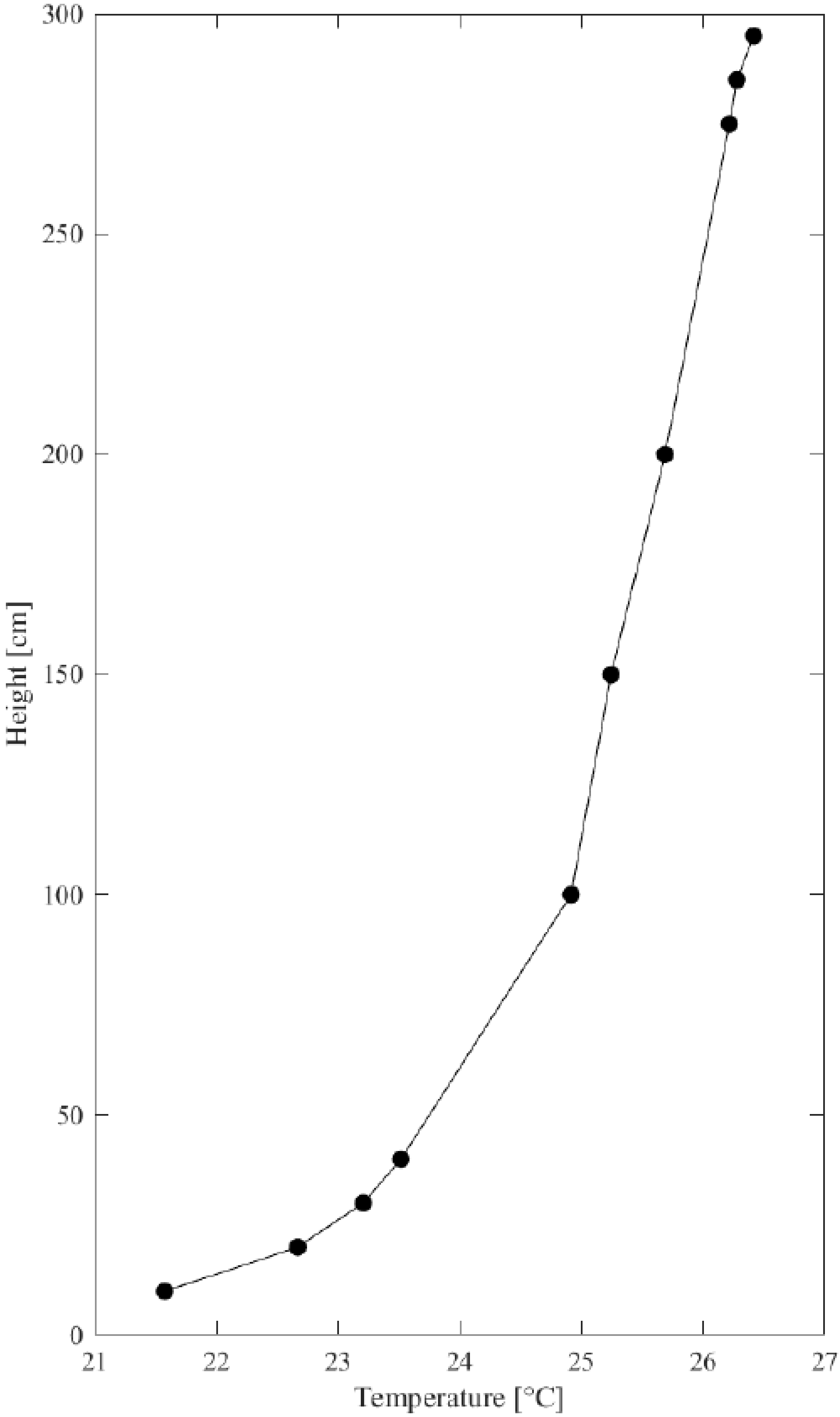

Figure 11: *Temperature gradient measurement at the vertical center-line inside the DSF cavity.*

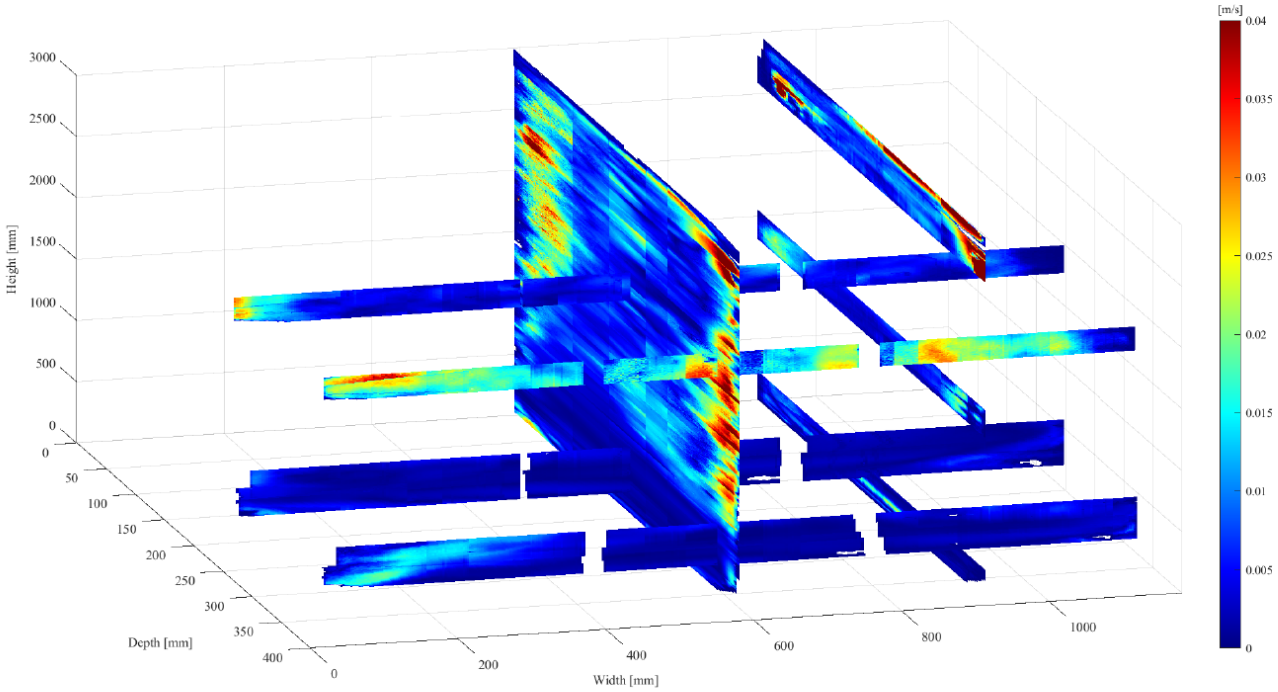

Figure 12: *PIV measurements of the air velocity field inside the DSF cavity.*

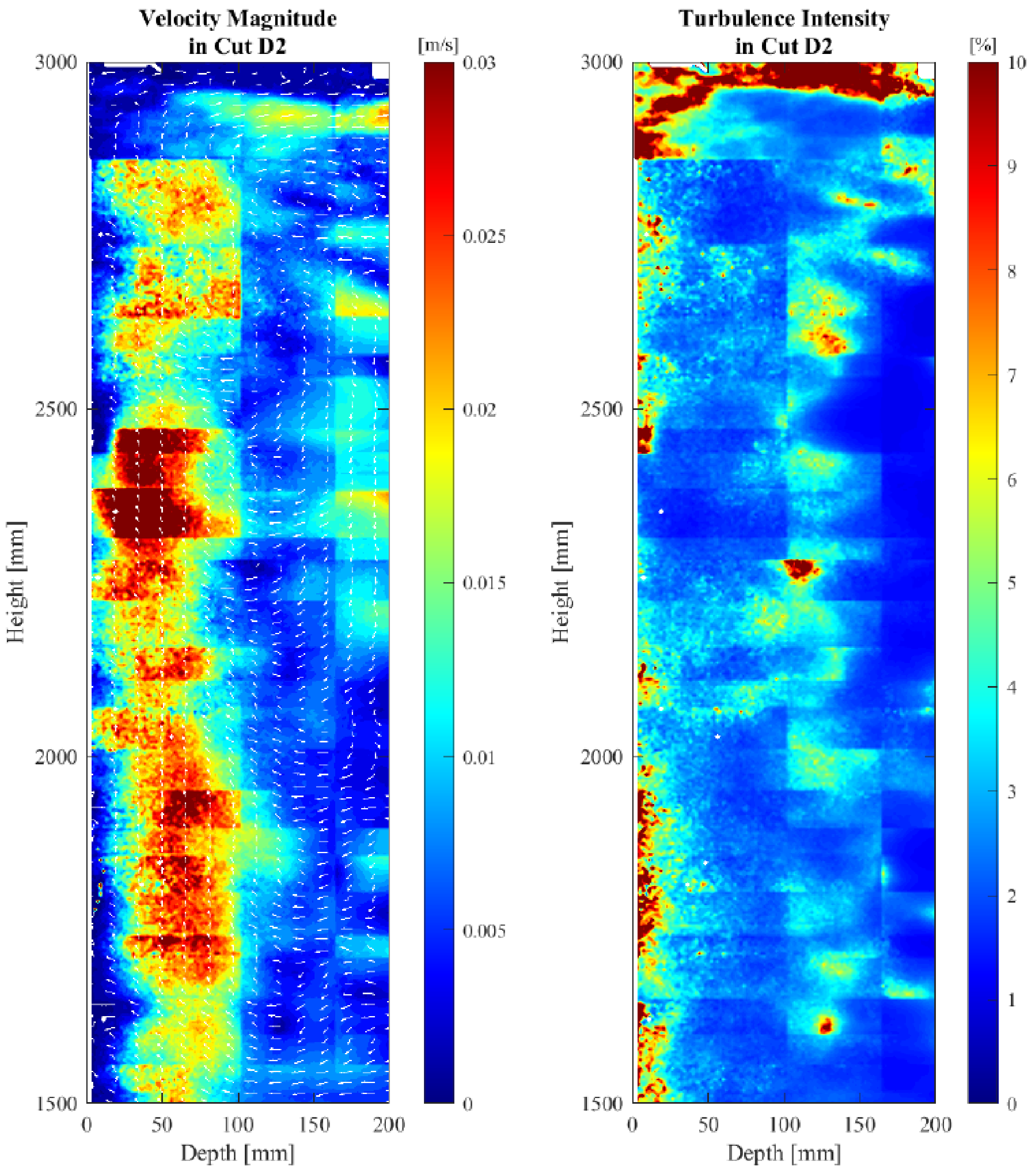

Figure 13: *Velocity magnitude and turbulence intensity on a side-view plane in the top half of the DSF cavity.*

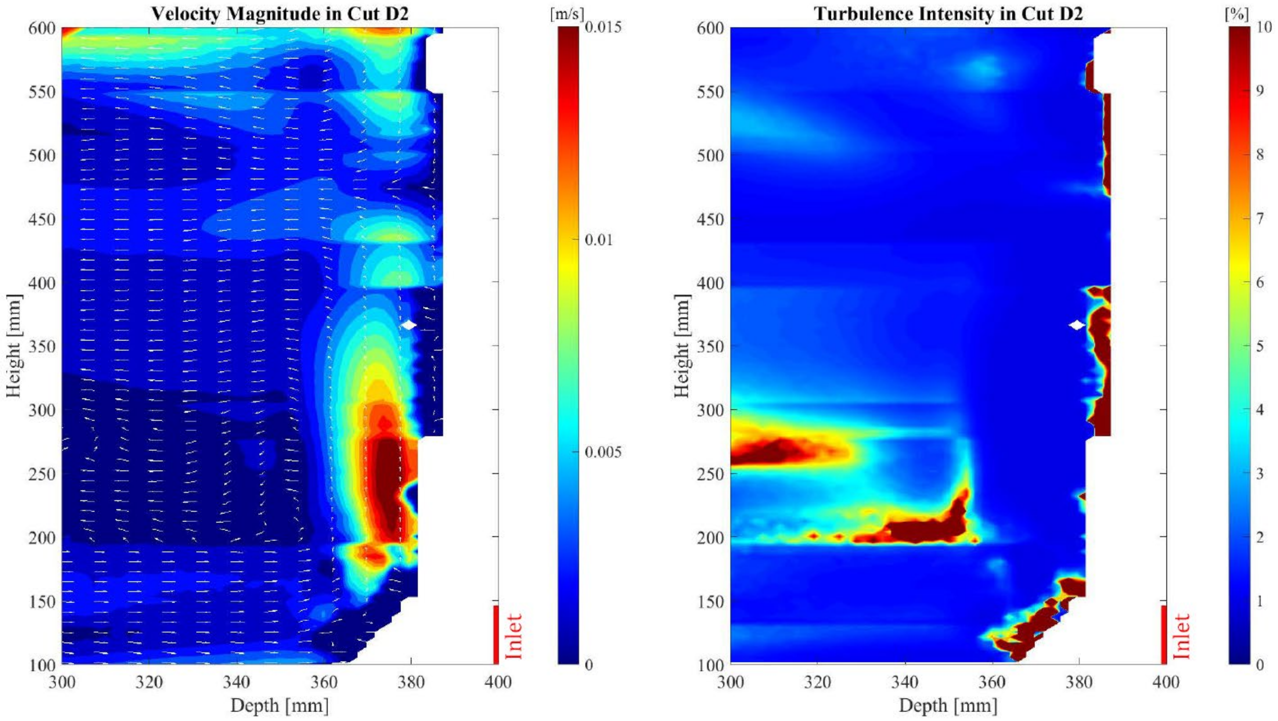

Figure 14: *Velocity magnitude and turbulence intensity on a side-view plane in the lower 0.6 meters of the DSF cavity near the air inlet.*

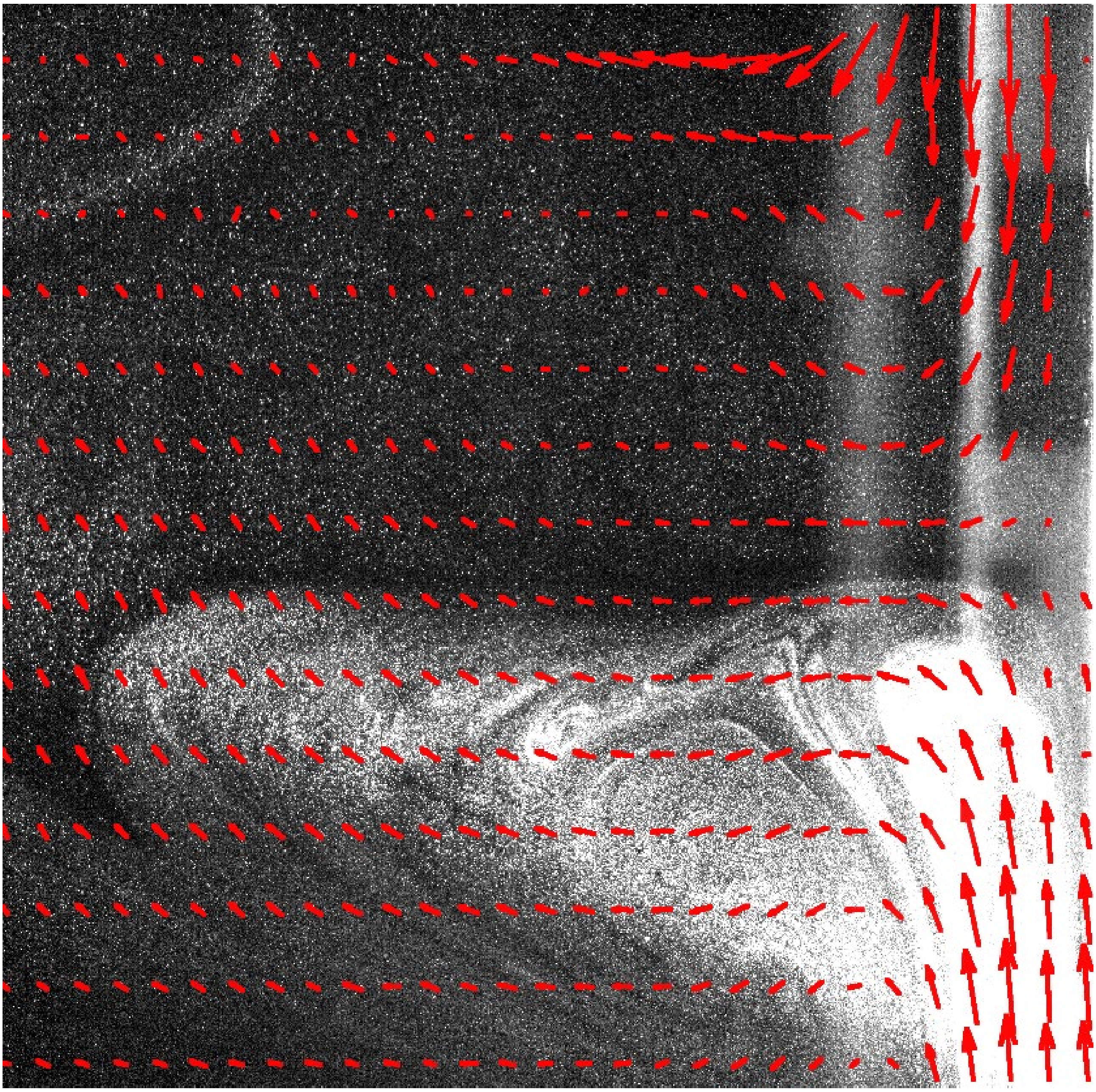

Figure 15: *Image of the stagnation point at the front wall.*

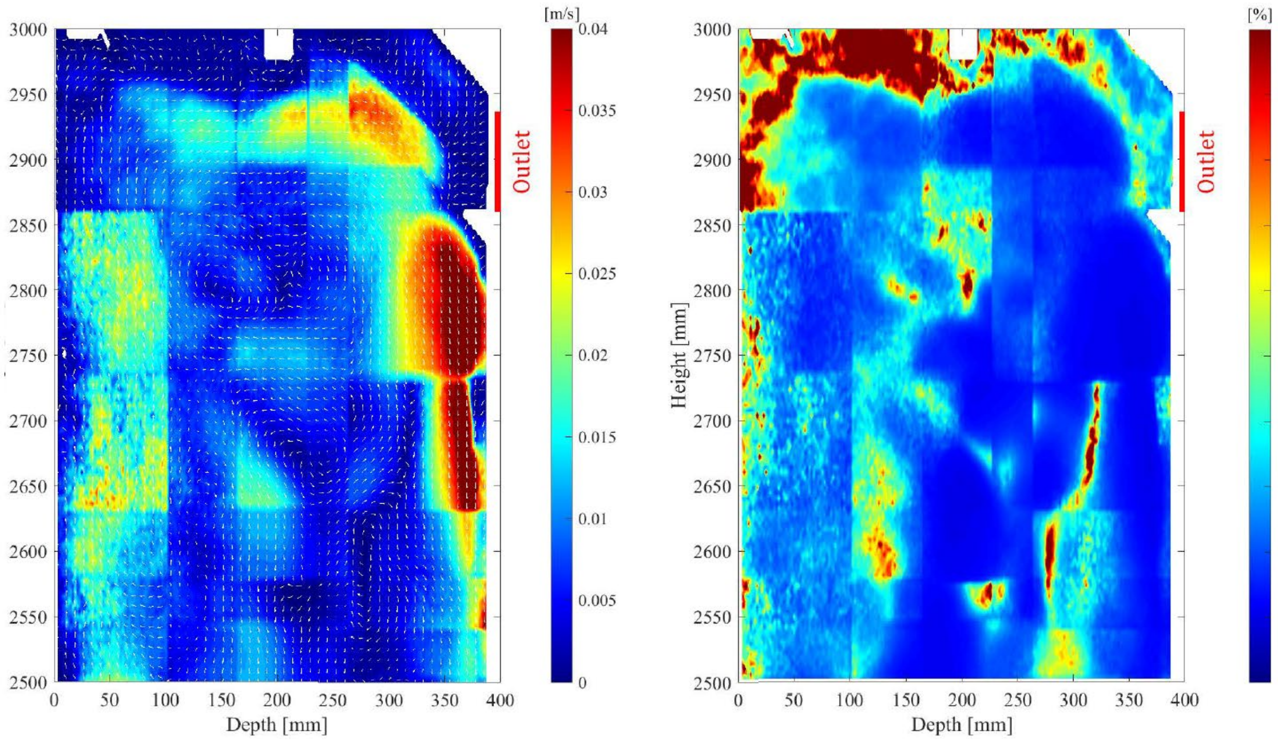

Figure 16: *Velocity magnitude and turbulence intensity on a side-view plane in the in the upper 0.5 meters of the DSF cavity near the air outlet.*

2.3. Future Upgrades of the DSF Flow Channel Setup

In this section, future upgrades and improvements for the DSF Flow Channel setup are presented. Those improvements will be implemented in the near future before conducting a new measurement campaign on the DSF Flow Channel experimental setup.

In order to improve PIV measurements, the back wall of the cavity will be repainted with a very dark and smoother coating to avoid the reflection of the laser beam which can create false seeding particles on the pictures recorded by the high-speed camera.

The current temperature control of the inlet air is performed by a hydronic cooling heat exchanger actuated by a motor-valve and connected to the cooling line of the laboratory which is supplied by large chillers (see *Figure 17*).

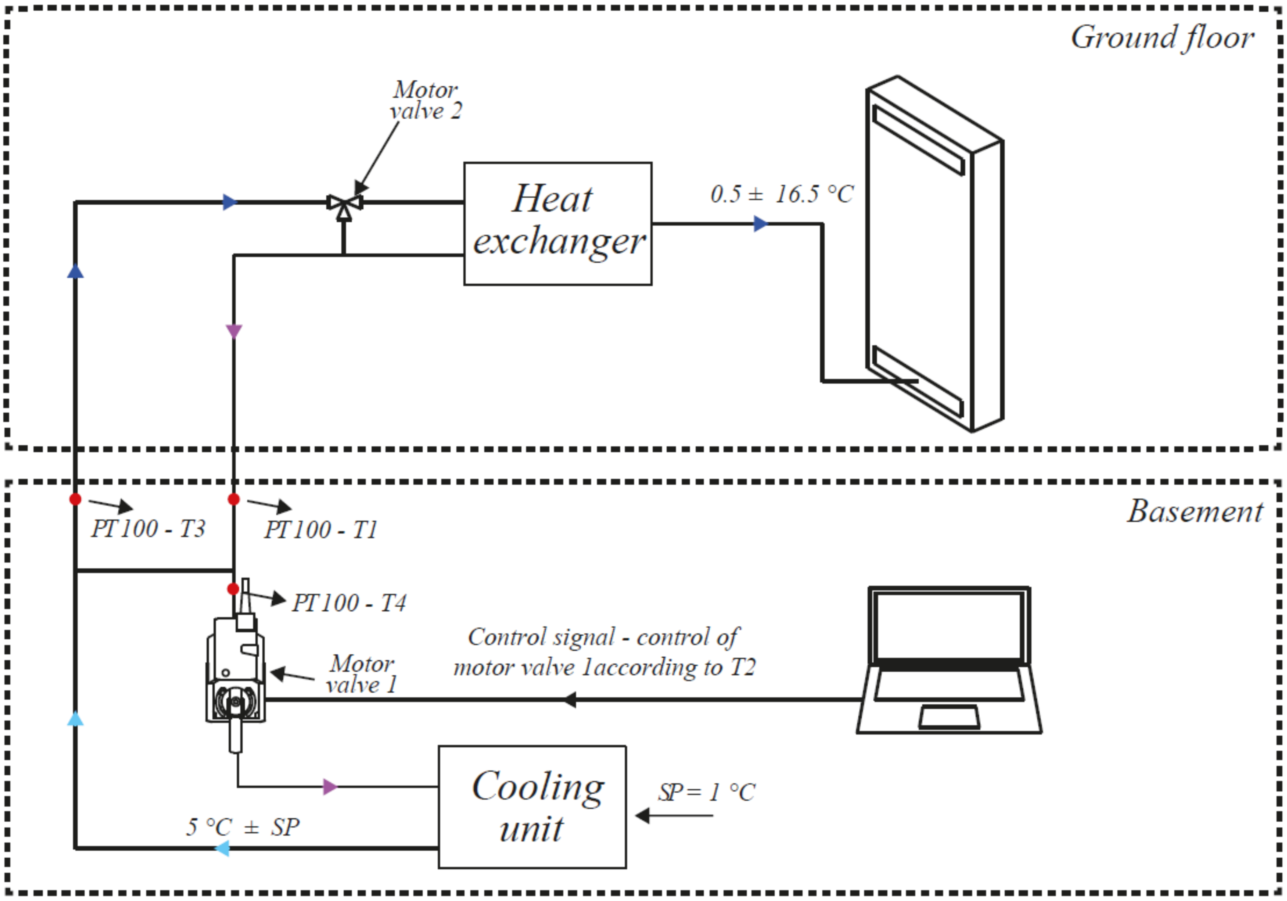

***Figure 17**: Current temperature control system of the inlet air to the DSF Flow Channel setup.*

Such a system can be difficult to control in order to keep a constant temperature of the inlet air in the case of low airflow rates. The disturbances of the ON/OFF cycles of the chiller units can be challenging to balance with such a heat exchanger and motor valve. For DSF Flow Channel experiments requiring low airflow rates and therefore low cooling power, the current hydronic heat exchanger will be replaced by an array of Peltier modules connected to heat sink heat exchangers arranged inside the supply airflow duct (see *Figure 18*).

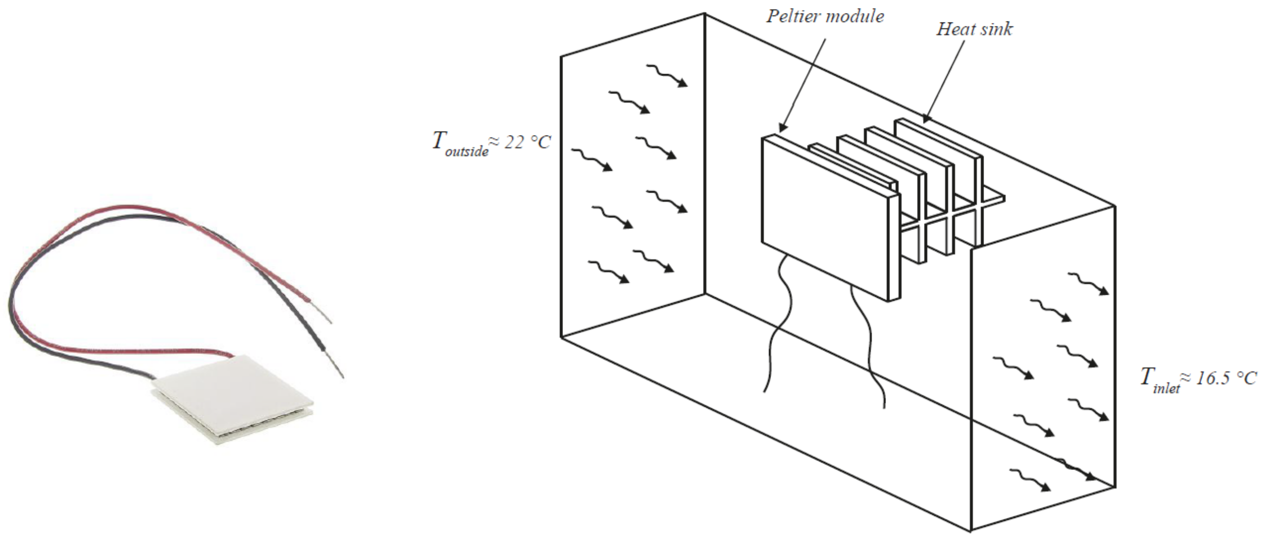

***Figure 18**: A 37.9W, 3.9A, 15.7V Peltier module (left); a suggestion of Peltier module-based cooling system for the air inlet supply to the DSF Flow Channel cavity.*

The current temperature control system of the heated back wall of the cavity is performed by several electronic PI controllers. It will be replaced by an integrated control system coupled to a computer interface developed with the LabVIEW programming environment.

The current traverse frame system that supports the laser and the camera requires manual operation to change the position of the latter. This traverse frame will be replaced by a parallel robotic system. This will ease and speed up the PIV measurement, and improve the accuracy of the results since manually adjusting the levels of the camera and laser is a procedure that is prone to human error.

3. DSF 23

3.1. Setup Description

The DSF 23 is a full-scale DSF experimental setup with a semi-exposed cubical ventilated cavity of internal dimensions **440 cm high**, **266 cm wide** and **64 cm deep** (see *Figure 19*, *Figure 20, Figure 21* and *Figure 22*).

Figure 19: *Outside view of the DSF 23 experimental setup.*

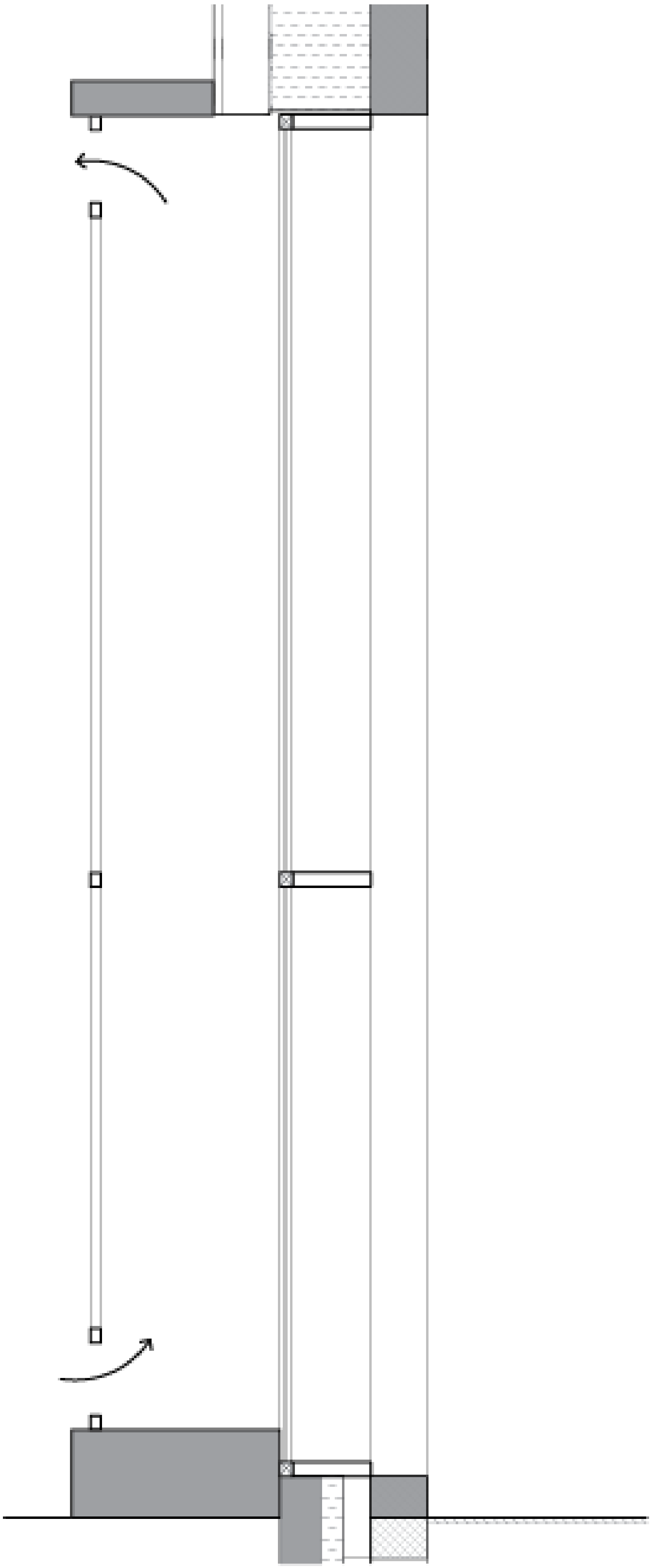

Figure 20: *Vertical cross-section view of the DSF 23 experimental setup.*

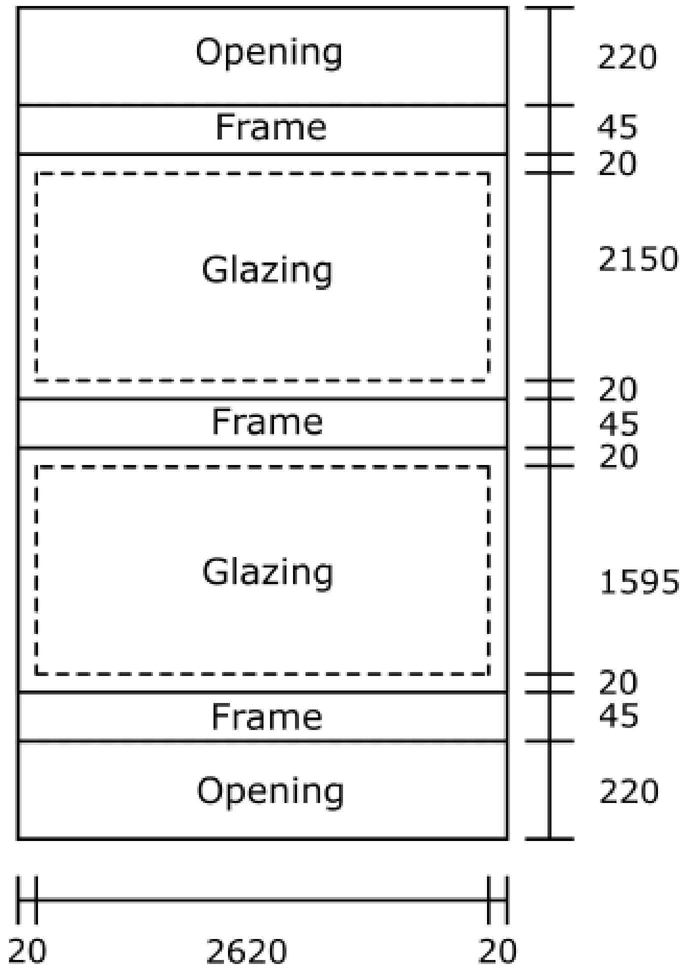

Figure 21: *Dimensions (front view) of the DSF 23 experimental setup (all dimensions are in millimeters) [1].*

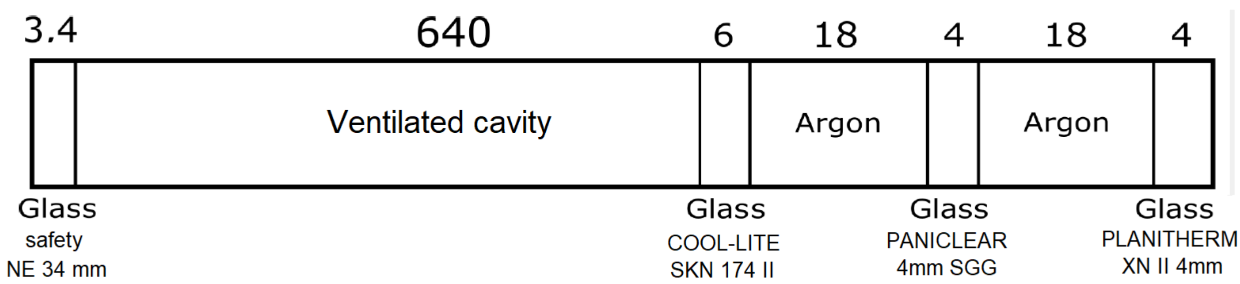

Figure 22: *Horizontal cross-section view of the DSF 23 experimental setup (all dimensions are in millimeters) [1].*

The inlet and outlet openings of the ventilated cavity are located on the top and bottom and have a rectangular shape with dimensions 2620 mm wide and 200 mm high (see *Figure 23*). There is no closing mechanism on the cavity openings.

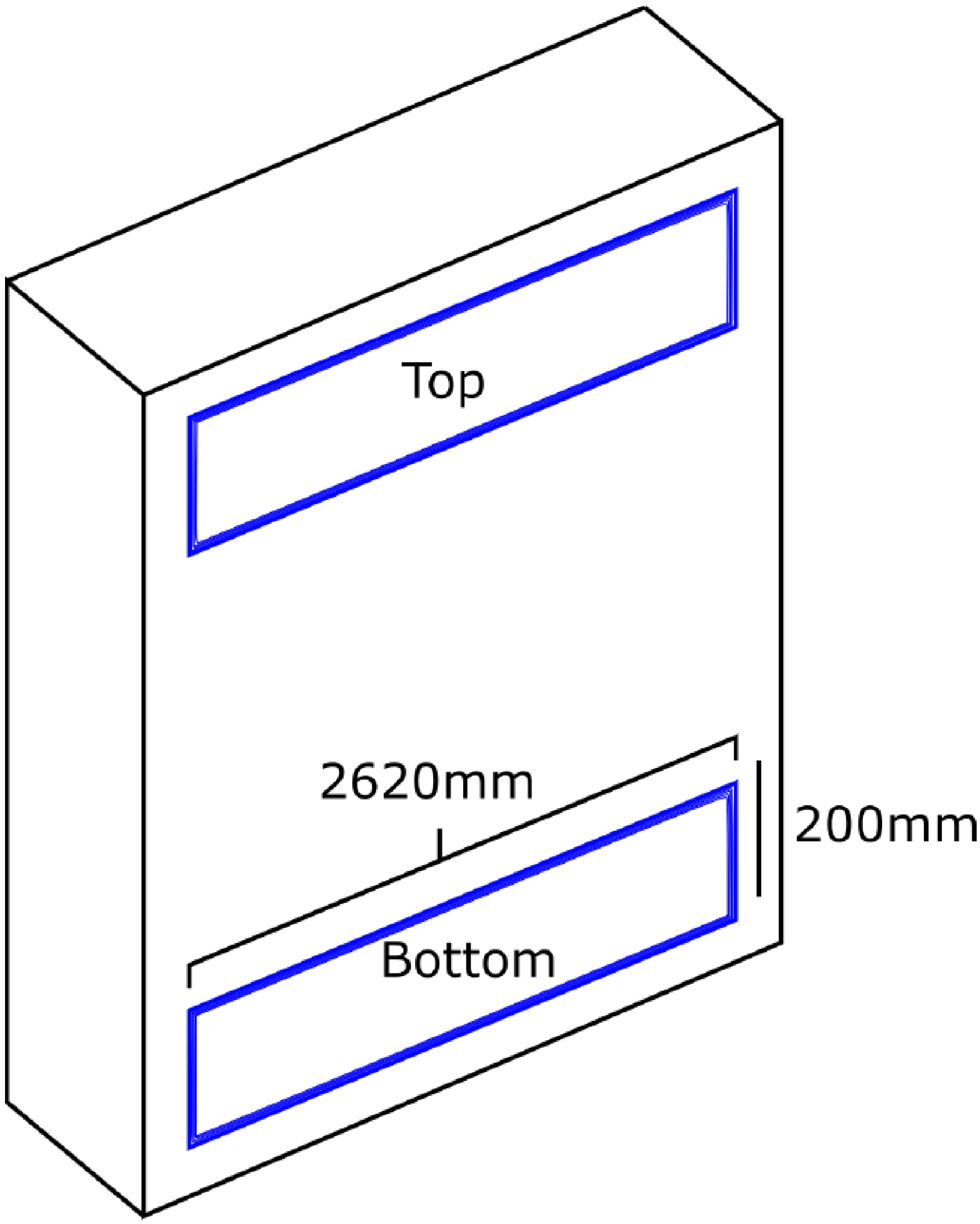

Figure 23: *Top and bottom openings in the ventilated cavity of the DSF 23 setup [1].*

The DSF 23 setup is located on the south façade of the laboratory building at BUILD - Department of the Built Environment, Thomas Manns Vej 23, 9000 Aalborg East, Denmark (see *Figure 24*, *Figure 25 and Figure 26*).

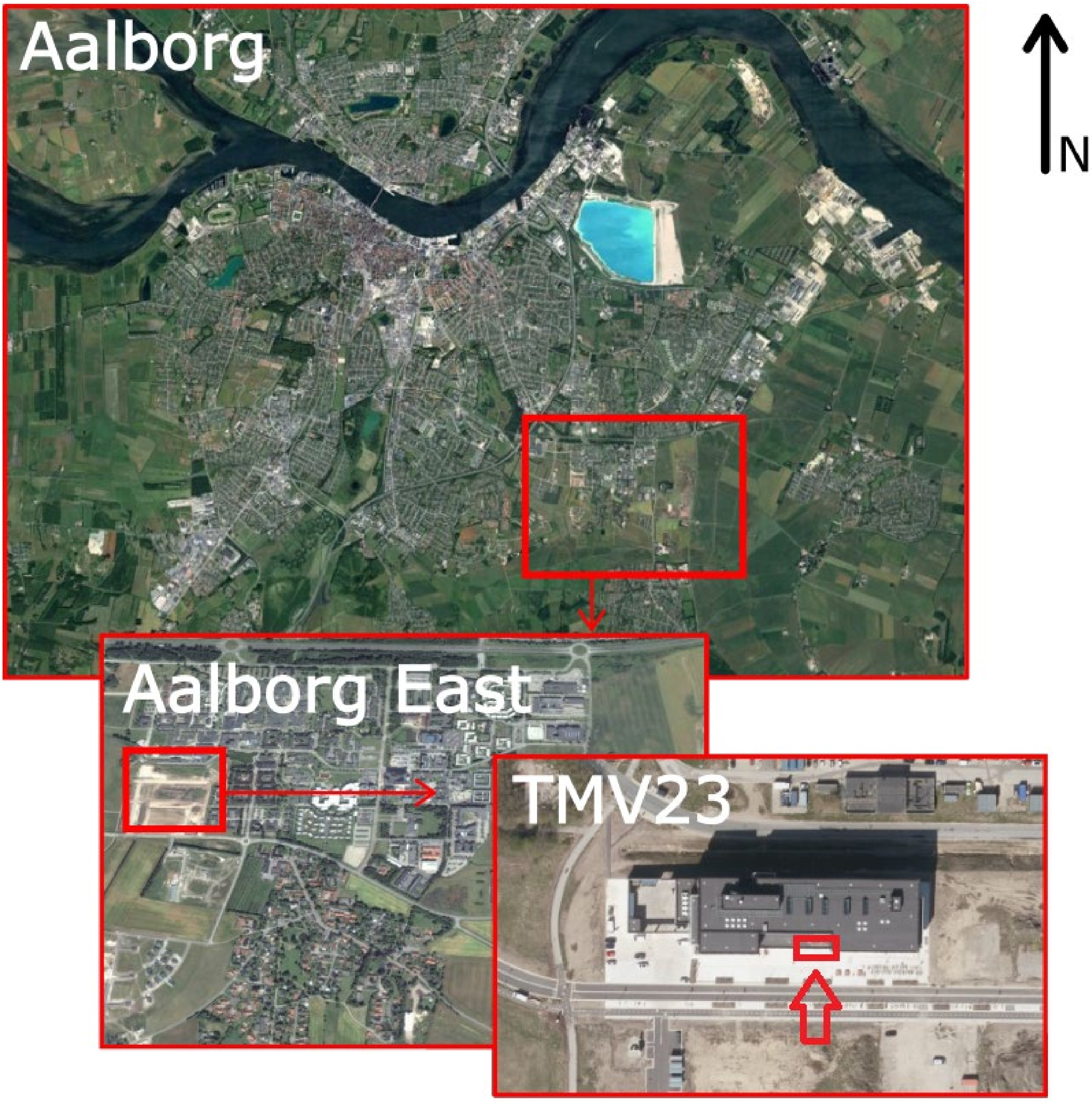

Figure 24: *Location of the DSF 23 experimental setup [1].*

Figure 25: *Front view of the DSF 23 experimental setup integrated into the south façade of the laboratory building at the Department of Civil Engineering of Aalborg University [1].*

Building site	
Degrees of longitude	9°58'17.051"E
Degrees of latitude	57° 0'52.352"N
Altitude	17m

Figure 26: *Building site location and altitude for the DSF 23 setup [1].*

As mentioned before, the DSF 23 experimental setup is semi-exposed to the outdoor environment (facing south). The indoor surface of the ventilated cavity is exposed to the laboratory environment where the temperature is kept constant at 22 °C. The weather conditions at the building site of the DSF 23 are measured by the university weather station installed on the roof of the building where the DSF 23 is located. Wind direction, wind speed, horizontal diffuse solar irradiation, horizontal total solar irradiation, vertical total solar irradiation, outdoor air temperature, outdoor relative humidity and outdoor atmospheric pressure are measured.

The trees in front of the building's south façade are assumed to be too small to interfere with the solar path reaching the DSF 23 setup, and too slim to have a significant impact on the local wind speed and wind direction. The ground in front of the DSF 23 setup is made out of light grey tiles. The latter has a reflectance of 30% (when dry).

During the experimental investigations conducted on the DSF 23 setup, the main measurements of the ventilated cavity are the air temperature inside the cavity, the surface temperature on the different glazing panes, and the airflow rate inside the ventilated cavity.

Since the temperature sensors are exposed to direct solar radiation, it important to shield them in order to perform accurate air and surface temperature measurements. The cavity air temperature is measured with type-K silver-coated thick thermocouples that are shielded with a ventilated (small electrical fan) silver-coated copper tube (see *Figure 27*).

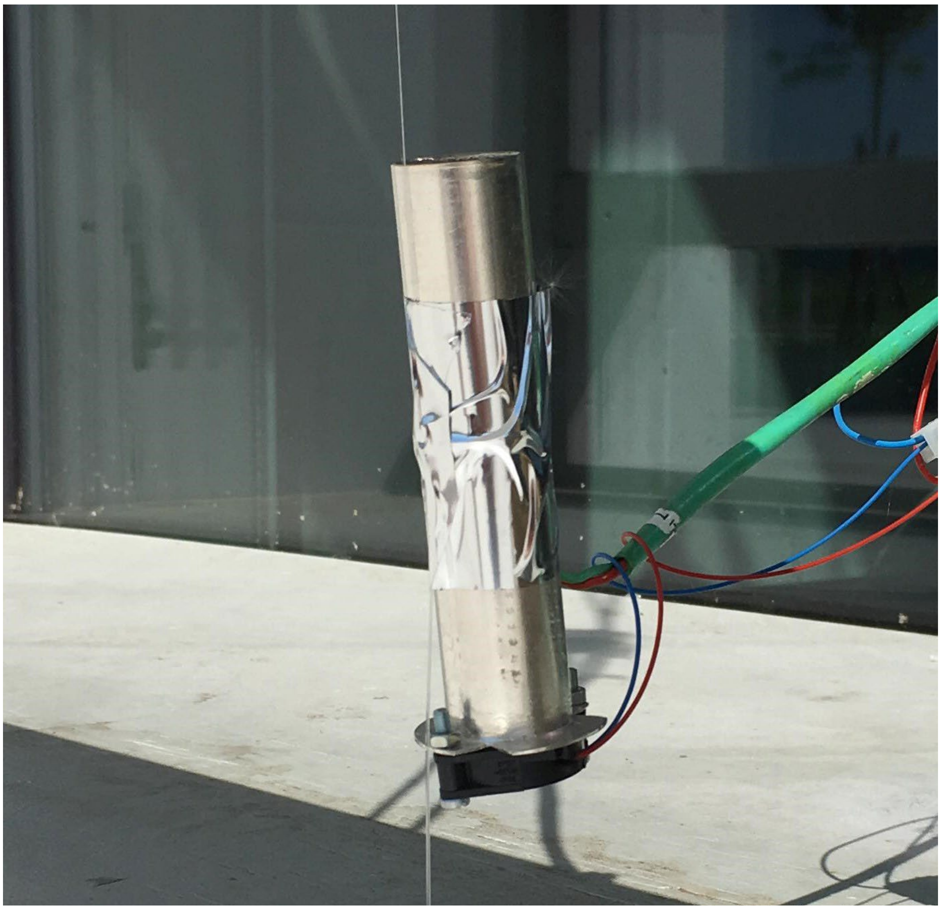

Figure 27: *Silver-coated thermocouple placed inside a shielding ventilated silver-coated tube for the accurate measurement of air temperature inside the DSF 23 cavity exposed to direct solar radiation. The small electrical fan for ventilating the shielding tube is set in extraction mode [1].*

Similarly, the type-K thermocouples used to measure the surface temperature in the DSF 23 setup are shielded from solar radiation with tinfoil (see *Figure 28*). The tinfoil shield is not touching the sensor, so the cavity it forms around it is well ventilated.

Figure 28: *Thick type-K thermocouples for surface temperature measurements in the DSF 23 setup [1].*

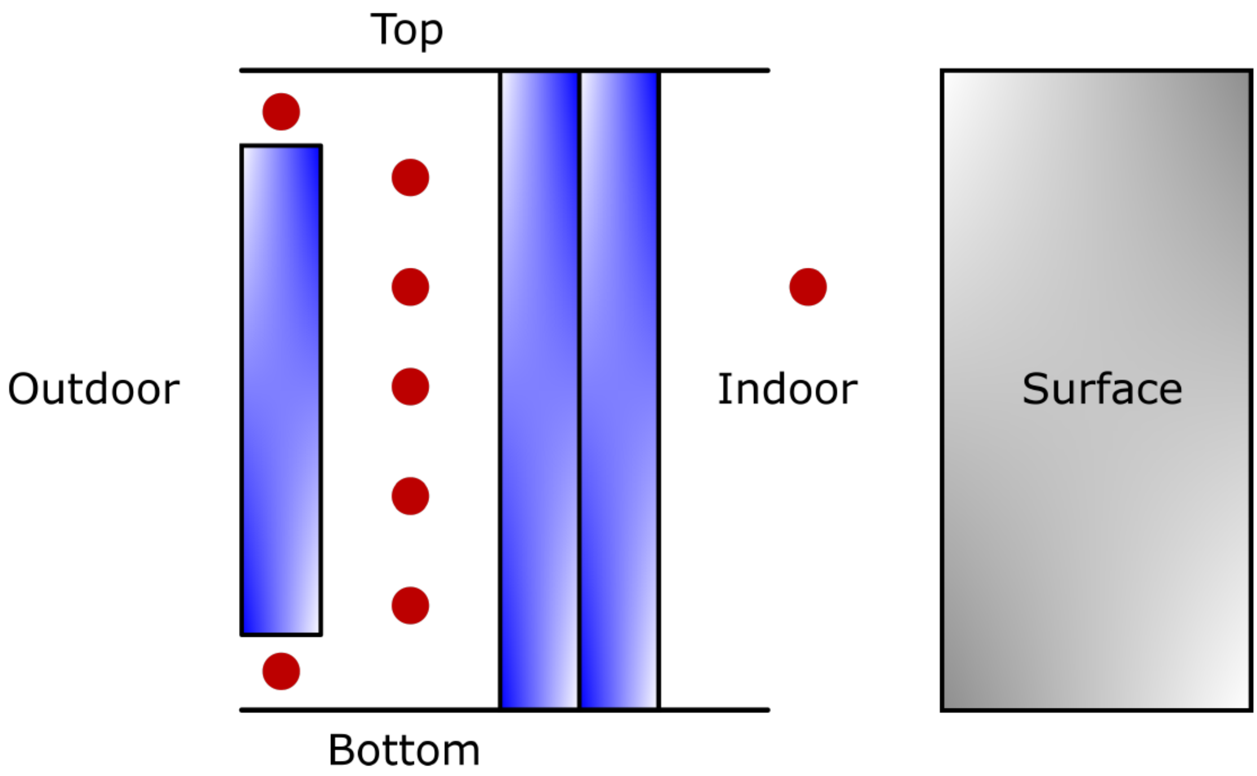

Figure 29: *Placement of thermocouples for the air temperature measurement in the cavity of the DSF 23 setup [1].*

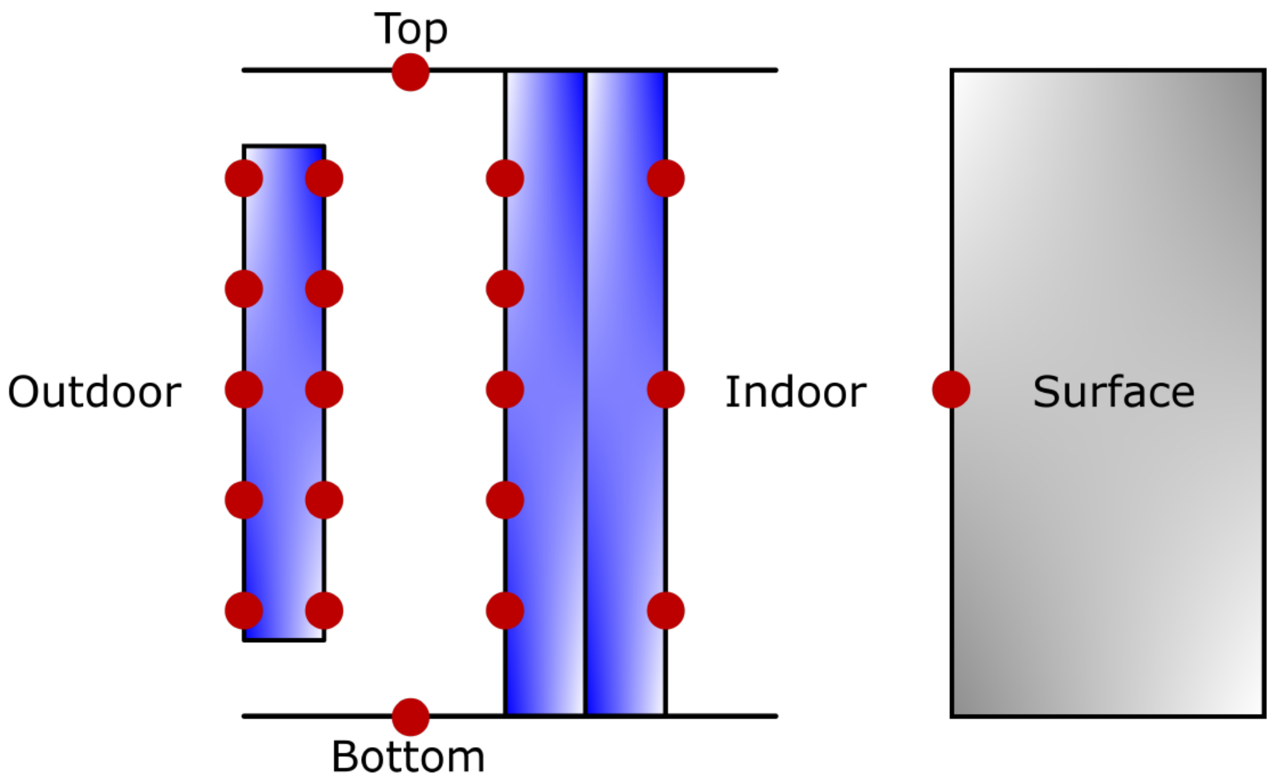

Figure 30: *Placement of thermocouples for the surface temperature measurement in the cavity of the DSF 23 setup [1].*

The airflow rate inside the cavity is measured with 2 ultrasound flow sensors from Lindab (Ultralink). The Ultralink airflow meter comprises a duct that is 315 mm in diameter. The sensor thus measures an average airflow across that section area. The 2 Ultralink sensors are placed at a height of 2.11 m from the bottom of the cavity. Each of them is in contact with an opposite side (front and back) of the cavity in order to measure the average airflow rate at the front and back boundary layers of the DSF.

Figure 31: *External view on the Ultralink air flow sensors (Lindab) in the ventilated cavity of the DSF 23 setup [1].*

Figure 32: *Internal view on the Ultralink air flow sensors (Lindab) in the ventilated cavity of the DSF 23 setup.*

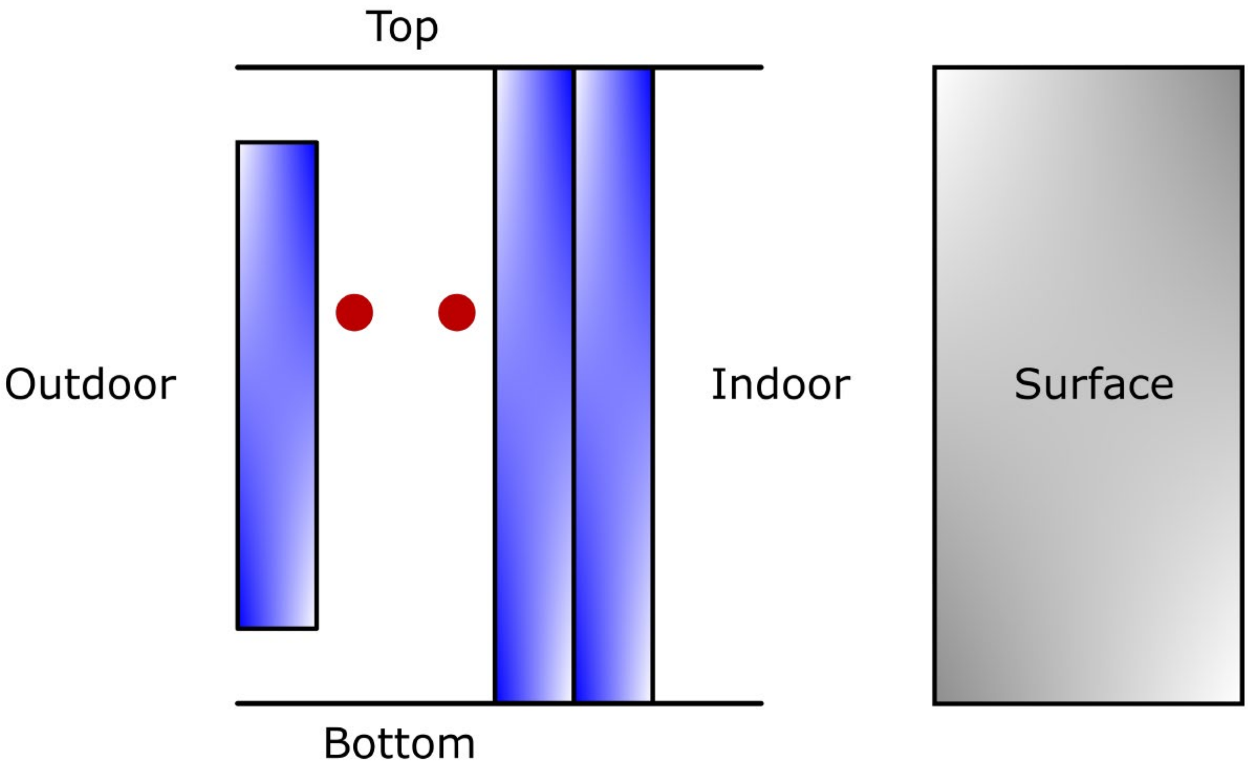

Figure 33: *Location of the Ultralink sensors for the measurements of the airflow rate inside the cavity of the DSF 23 setup [1].*

More information about the DSF 23 experimental setup can be found in the report of the latest investigation conducted on this experimental setup (Bernes and Dalsgarð, 2018 [1]).

3.2. Examples of Results from Experimental Investigations on the DSF 23 Setup

In the latest investigations carried out with the DSF 23 setup, the airflow and temperature measurements in the ventilated cavity were used to validate and calibrate a DSF numerical model (see *Figure 34*). One can see that the results from the calibrated model are in very good agreement with the measurements of the real DSF system [1].

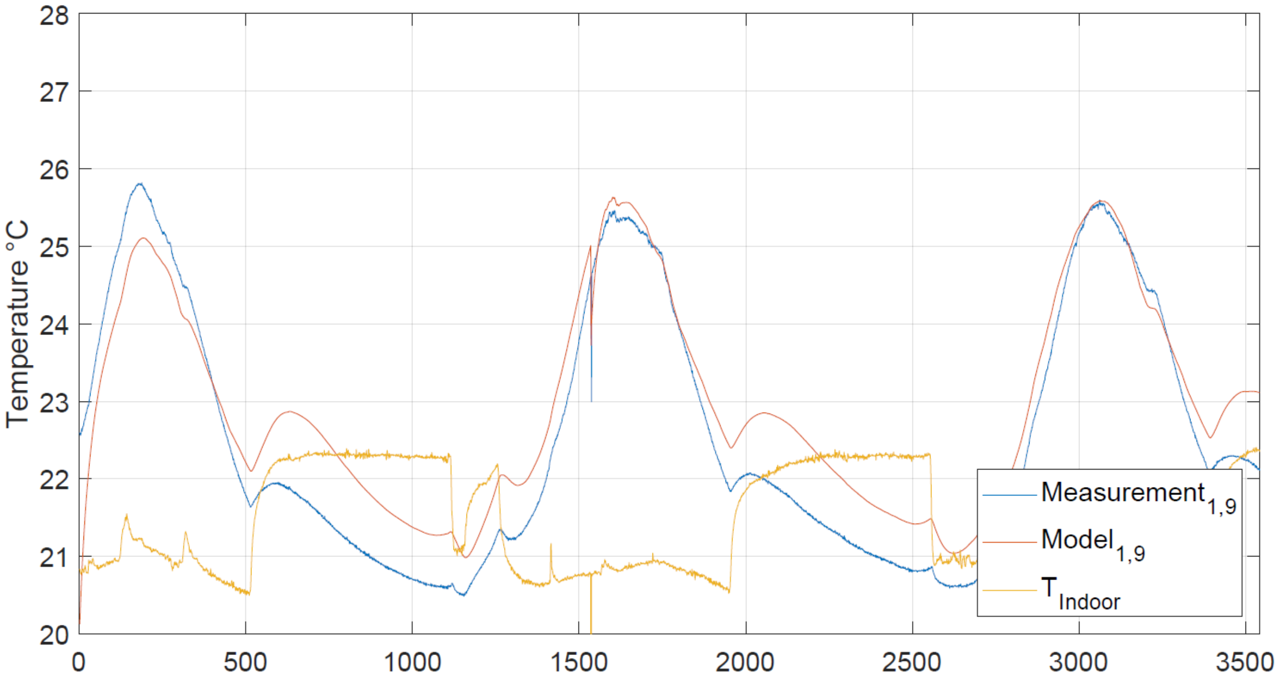

Figure 34: *Comparison between the temperature predictions of the calibrated DSF numerical model and the measurements inside the DSF 23 setup [1].*

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[1] Bjørn Steen Bernes, Búi Persson Dalsgarð. Dynamic Modelling and Measurements of a Ventilated Double-Skin Façade. Master thesis. Department of Civil Engineering, Aalborg University, 2018. https://projekter.aau.dk/projekter/files/281244219/Master_Thesis.pdf

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