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Experimentally Study the Temperature Profile in the Plume Chimney above a Natural Draft Chimney Model

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ABSTRACT

The chimney holds a central position in the industry, as the efficiency of the stack directly impacts the industry's overall performance. The presence of a real plume at the chimney exit indicates that the chimney is in draft-free operation. This study uses the temperature profile to detect a plume at the chimney's exit. To conduct experiments, the project entails designing and fabricating models for three distinct model chimneys. We modify the models by adding a wire mesh screen to face areas of 0.56 m^2, 1.00 m^2, and 2.25 m^2. This protects the cold inflow at the top to ensure the cold-inflow-free operation of the chimney. K-type thermocouples, linked to a data logger and a computer, measure the temperatures at the exit points and above them. The experimental results show that a wire mesh screen covering the chimney has established an effective plume at the chimney exit. Theoretically, we calculate the maximum effective plume height as 0.27 m above the chimney face, which allows us to measure the temperature up to 0.27 m on the vertical axis (y-axis). Industries, where waste heat rejection from the system is an important task, can use this information to develop an effective natural draft chimney.

Keywords: Natural Draft, Solar Chimney, Plume, Renewable Energy.

1 Introduction

Many industries, including power plants, wood processing plants, refineries, etc., now use chimneys to remove dust and smoke. There are two ways to drive a chimney: mechanically or naturally. A naturally driven chimney, also known as a natural draft chimney, Since the development of natural draft chimneys is one of the alternatives to mechanically assisted forced draft chimneys, the naturally driven chimney is the primary topic of this study. The natural draft chimney, which operates on the principle of natural convection, is based on free boundary flow phenomena such as forest fires, column expansion above high-altitude land, and plumes released from stacks [1]-[3].

The ambient and process sides of a natural draft chimney have different densities, which results in a pressure differential that drives airflow upward. If the air receives heat energy from a constant thermal source, like in a heat exchanger, natural convection will persist. As long as the cold air is present and unobstructed by another heat source, the constant heat transfer causes the air to warm and rise. Consequently, air constantly passes over a heat source. Thus, the following conditions set off the natural draft process:

On the process side, the temperature is higher than the outside temperature.

The hot air is constantly moving upward from the process side.

At the heat exchanger's air entrance, the rising passage of air creates damaging pressure.

At the heat exchanger's output exit, positive pressure builds up.

Warm air exits the building through the chimney, while cold air takes its place in the surrounding atmosphere. The heat transfer function acts as a nonstop heat supply until the flow reaches a steady state.

1.1 Natural Convection and Source of Heat

Describing the plume or flow of air above a pure source of heat energy or heat exchanger using a straightforward normal convection process is challenging since the plume's behavior relies on the specific attributes of the heat source and its surrounding environment. The literature review identified two primary types of natural convection plumes: free and wall-supported. The upward flow above a horizontal plate identifies a free plume, while a vertical plate heat source causes a natural convection plume or upward flow. Researchers have conducted extensive research on plumes originating from both line and point sources. Leu and Jang [4] talked about plumes that appear above a localized heat source. As the temperature rises, the centerline velocity decreases. However, as the temperature dispersion coefficient increases, both the temperature and velocity at the centerline decrease.

Recent findings indicate that the temperature of a pure heat source does not affect the overall change in air velocity. The empirical equation developed by Byram and Nelson [2], which relies on mass balance, does not provide information regarding the plume's shape or the distribution of temperatures in the flow establishment zone above the heat source. Furthermore, a pure heat source is defined as one that does not emit any byproducts of combustion while generating heat and remains unaffected by external factors, such as geographical conditions.

1.2 Plume (Partial) Chimney

Fig. 1 illustrates the function of a standard chimney, which uses a wall or tower to block hot air from the heat source. This creates a difference in buoyancy and allows for airflow.

In the 1930s and 1940s, Zeldovich and Schmidt invented the use of point or line sources to simulate cooling mechanisms for electrical devices. The majority of studies on plume discharge

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from chimneys focus on the dispersion of stack effluent, the environmental impact on cooling towers, and the development of cooling systems [5]-[8],[9].

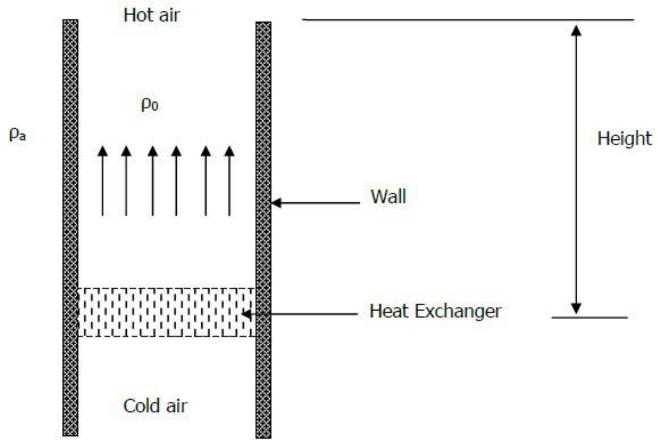

Fig. 1 Airflow pattern in a normal solid-walled chimney

1.3 Temperature Profile in the Plume Chimney

The plume's parameters determine the area where the flow forms above the hot plate. A plume is an unrestricted movement of a substance that originates from a heat source and constantly releases energy. Buoyancy forces propel the plume. Therefore, a plume can only travel vertically, either upwards or downwards, depending on the current conditions [10].

Zinoubi *et al.* [11] analyzed the thermal dispersion in a cylinder and investigated the interplay between a plume and a thermosyphon. Zinoubi *et al.* [11] conducted a study to improve the effectiveness of industrial chimneys. As part of their investigation, they established the temperature distribution within a cylindrical object. The plume axis experiences a decrease in average temperature as a result of cold air infiltration from the external environment. Conversely, when the cylinder approaches the heat source, the temperature profile shows that the point with the highest temperature shifts towards the vertical axis [12]-[13]. Turbulence arises when there is a stable temperature profile at a higher altitude with no cold air infiltration. The study might refer to cold air penetration as the entry of air from above into the system [11].

2 Experimental Method

To carry out the experiments in the lab, an air inlet duct is constructed according to the design depicted in Fig. 2. In this project, we tested three models of chimneys with two different categories, one with and one without a solid wall chimney, heights of 0.3, 0.6, 0.9, and 1.2 meters and with heat loads of approximately 1.0, 1.5, 2.0, and 2.5 kilowatts. The study's goal was to determine how the plume chimney's temperature developed from the various size-point heat sources along the vertical and horizontal axes. As a result, there are three distinct face areas for heat sources or chimneys. Seven K-type thermocouples monitor the plume's temperature while conducting the experiments under various heat loads.

2.1 Range of Temperature Measurements

The solid-walled chimney was located on top of the electric heater. The solid-walled chimney maintained constant heights ranging from 0.3 m to 1.2 m. The main instruments were a voltmeter, a clamp multi-meter, a vane anemometer (model LC-430 VA), a Furness Controls (model FC-0320) differential, and twelve Type-K thermocouples. To measure the average temperature, we place five thermocouples inside the solid-walled chimney and seven in the plume chimney. We also connect the electric resistance in series or parallel to generate varying heat loads, as the temperature on the process side dictates both the differential pressure and the velocity.

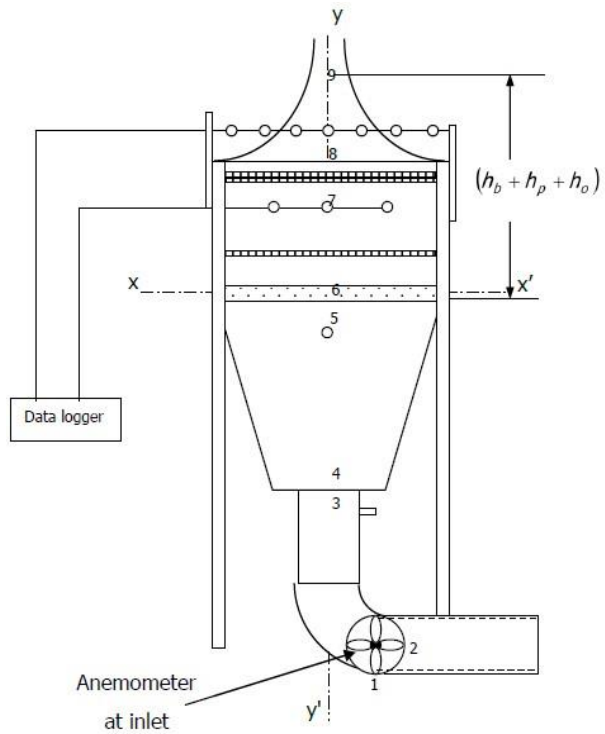

Fig. 2 Experimental rigs to determine the temperature in the plume chimney

2.2 Experimental Setup

K-type thermocouples are used to measure the temperature during the experiments. The thermocouple readings are compared with those of a conventional thermometer to identify the measurement errors. The thermocouple readings' inaccuracy ranges from +3 K to -2 K. We recorded the temperatures in the zone of flow establishment using a total of seven thermocouples at seven separate locations. The position of the thermocouples was evenly apart and fixed from side to side between two angled bar supports. Another five thermocouples were positioned within the solid-walled chimney. Fig. 3 illustrates the placement of four thermocouples at the midpoint between the center and the corner, and one thermocouple at the center. Two Cole-Parmer USB Data Acquisition Modules are connected with the thermocouples and the computer to obtain data directly from the system. Once all the instruments are installed in the testing duct, the experiments could be undertaken.

2.3 Experimental Procedure

The data logger immediately connected each thermocouple to the computer, enabling direct temperature monitoring at every location. Once the output temperature reached a constant state, the system automatically recorded the temperature in the flow setup zone and the solid wall chimney. According to preliminary research, the height of the plume chimney above a small hot plate was negligible; nevertheless, it may range from 0.1 m to 0.2 m over a large plate or in a full-size air-cooled heat exchanger [12].

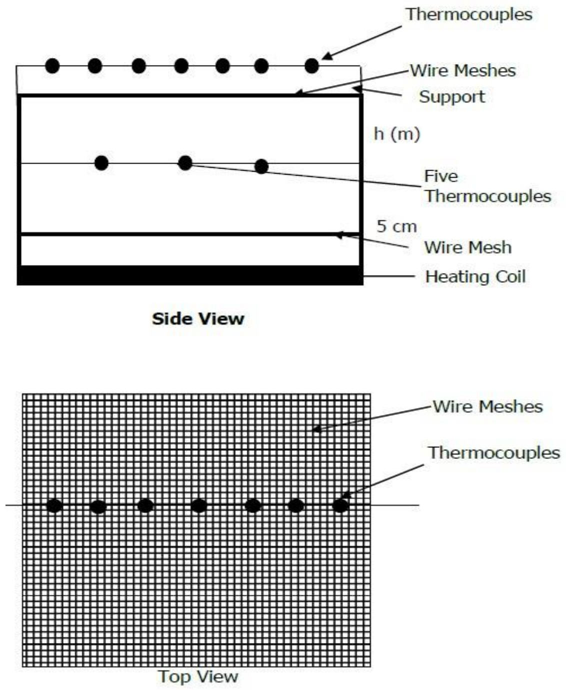

Fig. 3 Arrangement of thermocouples

Therefore, as shown in Fig. 4, we recorded the temperature at 10 distinct heights within the flow establishment zone, starting at 3 cm and increasing by 3 cm each time.

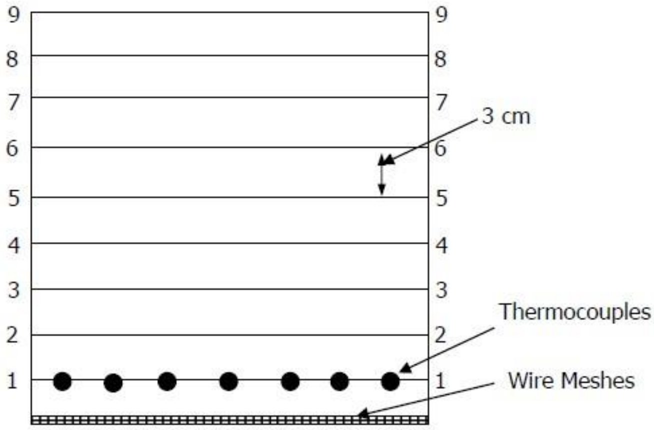

Fig. 4 Temperature measuring location above solid wall chimney

During the experiment, the computer automatically recorded the temperature readings at 30-second intervals for five minutes at a time to ensure high precision from the seven thermocouples in the flow-establishing zone. After five minutes, the thermocouples moved to different heights in the flow establishment zone. To ensure accuracy, each reading required three duplicate readings, and then the average value was recorded in a tabular manner for further study.

3 Results and Discussions

Table 1 shows an overview of each model's experimental setup and experiment design. After completing all trials using configurations A, B, and C, we consider configuration C to measure the temperature profile in the flow zone due to its superior performance compared to other models. In this configuration, the average heat load was a minimum of 1 kW and a maximum of 2.44 kW, and the chimney model's face areas were 0.56 m^2, 1.00 m^2, and 2.25 m^2. We maintain the solid wall chimney heights at 0.3 m to 1.2 m and measure the horizontal axis (x-axis) temperature at seven locations above the face area of the chimney model. The vertical axis's location started at 0.03 m and continued until 0.27 m, with an increment of 0.3 m. The research articles by Rahman et al. [13] show the details of the calculation and effective plume chimney height (EPCH).

Table 1 Configuration for Experiments

Configuration	Solid Wall Chimney	Wire Mesh Screen
A	No	No
B	Yes	No
C	Yes	Yes

Fig. 5–Fig. 10 show the temperature at the flow zone, which fluctuated between 35ºC and 65ºC along the y-axis direction at 0.03 m and 0.27 m. These temperature fluctuations result from changes in face areas, an increase in heat loads, and an increase in the height of the solid wall chimney. The experimental results also show that the different solid wall chimney heights influence the flow zone temperature distribution. The magnitude of the zone of flow temperature at seven locations is more stable when the solid wall chimney height is 1.2 m high. The exit air velocity and air temperature, known as buoyancy effects, generate the plume above the chimney model. When surrounding air velocity or turbulence can penetrate the plume, it starts to break. At the same time, the exit air temperature drops significantly. Therefore, the effective plume chimney is present until the exit air temperature is constant [14]. In this project, we measured temperature only because, in the natural convection process at low heat, the air velocity is very low and difficult to measure. Furthermore, we can estimate the air velocity by comparing the temperature difference between a plume and a solid-walled chimney. At a low solid chimney height, we observe the unstable plume as the face area of the chimney increases.

This is because, in this study to overcome the effect of cold in flow or flow reversal a wire mesh screen is used. The wire mesh screen has significantly enhanced the exit air temperature or temperature of the air at the solid wall chimney as a result buoyancy force enhanced the exit air velocity which create more turbulence at the exit of the wire mesh screen. The effect of wire mesh screen can be described by the numerical work by Sharman *et. al.* [15].

Sharman *et. al.* [15] conducted a study to ascertain the average and varying lift and drag coefficients for various cylinder spacings, like a wire mesh screen. When the spacing exceeded five times the critical amount, the fluctuating forces increased significantly. On the downstream cylinder, there is a single reattachment and separation point for low velocity. The researcher conducted a comparison of the average and varying surface pressure distributions, accounting for the distance between the cylinders and the low Reynold number ranging from 10 to 200. There was a considerable difference in both the average and varying pressures between the cylinders located upstream and downstream. The pressures also varied depending on the cylinder spacing [15]. Additionally, we compare the center line temperature flow zone or plume chimney to the solid wall chimney's outlet temperature to confirm the presence of the plume chimney.

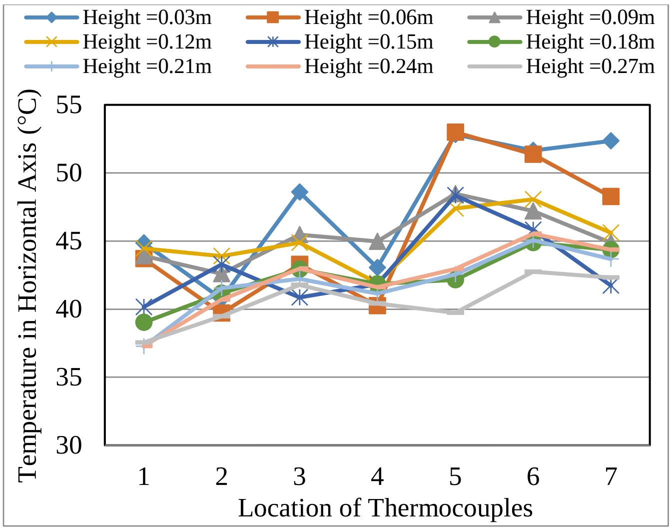

Fig. 5 Temperature Profile in the flow zone for Average Heat Load 2.33 kW Face Dimension 0.56 m^2 and Solid wall chimney Height 0.30 m.

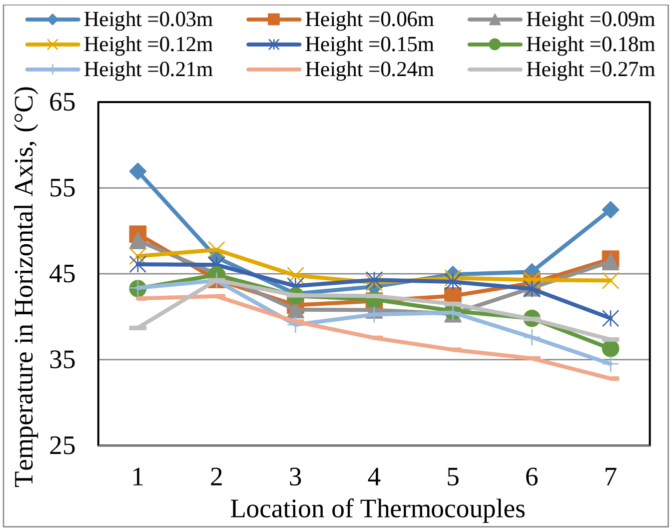

Fig. 6 Temperature Profile in the flow zone for Average Heat Load 2.34 kW Face Dimension 0.56 m^2 and Solid wall chimney Height 1.20 m.

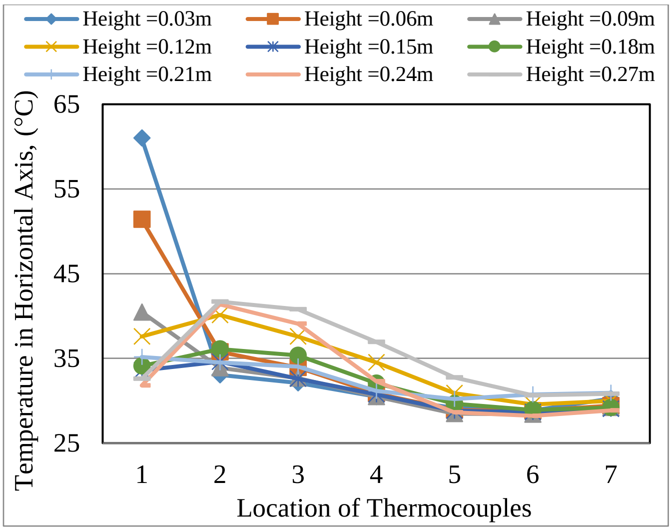

Fig. 7 Temperature Profile in the flow zone for Average Heat Load 2.60 kW Face Dimension 1.00 m^2 and Solid wall chimney Height 0.3 m.

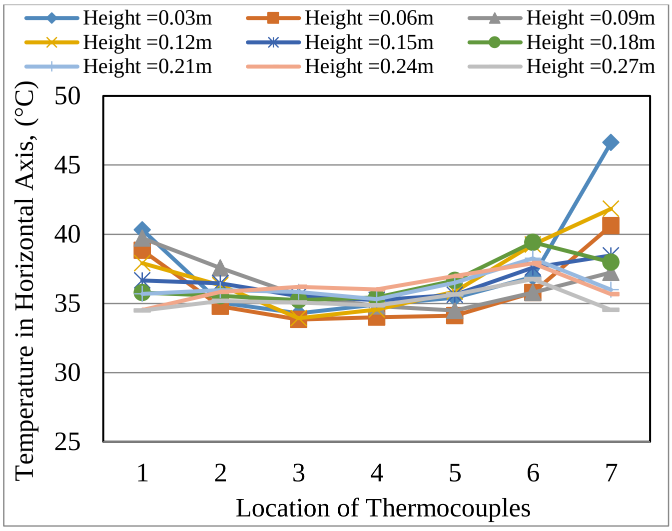

Fig. 8 Temperature Profile in the flow zone for Average Heat Load 2.44 kW Face Dimension 1.00 m^2 and Solid wall chimney Height 1.20 m

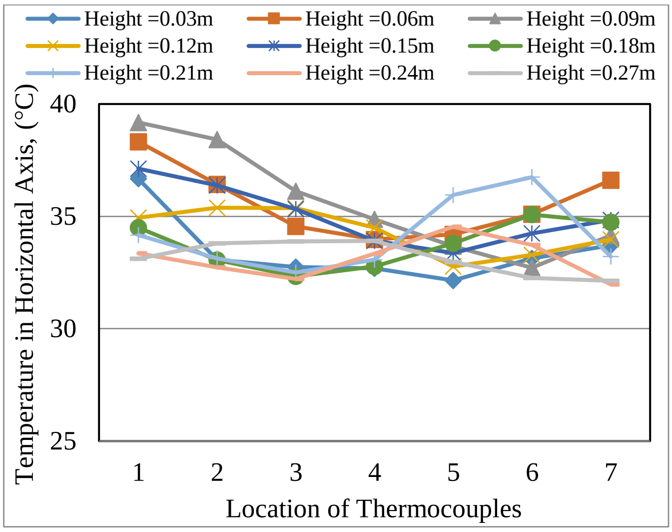

Fig. 9 Temperature Profile in the flow zone for Average Heat Load 2.42 kW Face Dimension 2.25 m^2 and Solid wall chimney Height 0.3 m.

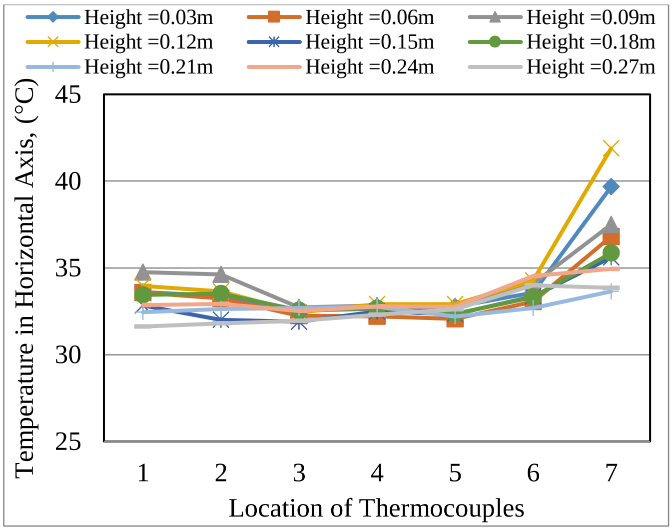

Fig. 10 Temperature Profile in the flow zone for Average Heat Load 2.52 kW Face Dimension 2.25 m^2 and Solid wall chimney Height 1.20 m

The findings demonstrated that the ratio of the solid wall chimney outlet temperature to the center line temperature is lower at the 0.3 m solid wall chimney and higher at the 1.2 m solid wall chimney. Except for those without a solid wall chimney, the ratio between the temperature of the exit air and the solid wall chimney was larger in a 0.05 m solid wall chimney due to the lower temperature of the exit air over the solid wall chimney. The study by Zinoubi *et al.* [11] on plume thermosiphon interaction, which also discussed the temperature profile inside a cylinder, provides a clear explanation for this phenomenon. The research aimed to enhance the efficiency of industrial chimneys, yet it also identified the essential flow characteristics.

4 Conclusion

The experimental results demonstrated that the horizontal temperature in the flow zone in the models' faces (0.56 m^2, 1.00 m^2, and 2.25 m^2) was nearly flat for the solid wall chimney with a wire mesh screen protector. Placing wire meshes in the chimney model significantly increased the solid-wall chimney outlet temperature. It demonstrated a stronger stack effect for wire meshes at the top of the solid wall chimney. The temperature difference between the solid-wall chimney and the plume is significantly higher, yet the centerline temperatures remained nearly identical up to 0.27 m, indicating a reduced impact from entrainment air in the system and the presence of plumes in the model chimney. It is also observed that the wire mesh screen's effect on chimney exit air velocity disturbs the plume chimney in a 0.3-meter solid wall chimney, while the plume chimney in a 1.2-meter solid wall chimney remains more stable. The wire mesh screen disturbs the exit air at low heights, causing turbulence at upstream.

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