Modeling air and fire non-stationary whirls in laboratory conditions

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Abstract. This study demonstrates generation of wall-free non-stationary air and fire whirls under laboratory conditions without using mechanical swirling devices and estimates their integral parameters. A simple experimental facility for the generation of concentrated air and fire vortex structures by creating unstable stratification and solid fuel combustion (urotropine) is described. With the use of photography, some data on the generation conditions and integral parameters (lifetime, height, and diameter) of air and fire whirls have been determined.

1. Introduction

Swirling (vortex) flows are widely spread in nature (atmospheric cyclones, tornadoes, dusty devils) and find numerous engineering applications [1, 2]. Simulating dust devils and tornadoes in laboratory environments is not a new concept. Many laboratory simulator designs were built for meteorological purposes to understand the parameters influencing dust devil and tornado formation [3-9].

In the simulation of a standing tornado near ground, there are two essentials factors: circulation and updraft. In the earliest works by Ying and Chang [3] and Wan and Chang [4] at the Catholic University of America, the circulation was produced by bringing air radially inward through a rotating cylindrical screen, and the updraft was generated by an exhaust fan at the opening of the top hood along its axis. In this way, both the circulation and the updraft can be controlled separately. The strength of circulation is controlled by the rotational speed of the cylindrical screen and the rate of the updraft can be controlled by the exhaust flow rate of the fan.

Ward [5] was the first to simulate main characteristic features of tornado in the laboratory such as a characteristic surface pressure profile, a bulging deformation on the whirl core and multiple whirls in a single convergence system. The apparatus consists of a cylindrical container of 8 ft in diameter in combination with a rotating mesh wire on the side and a fan affixed on the top of the cylinder. The fan power can regulate the volumetric flow rate, simulating the strength of the updraft. The rotation of the mesh wire is intended to simulate the ambient rotation in the atmosphere.

In the later works at the Purdue University [6, 7] the similar tornado generator was used. In the Purdue simulator, the four critical quantities, i.e., depth of inflow, radius of updraft hole, volume flow rate and far-field tangential velocity, are variable over a wide range of values. The primary goal of these studies (like in above mentioned works) is to produce the maximum stable whirl to produce quantitative measurements.

The simulator of wall-free whirls was created in Iowa State University [8, 9]. The fan motor and turning vanes were used to create the vertical flow with dry ice supplied for its visualization. The simulator design allowed moving the generated whirl structure along the ground. So, this enabled testing the interaction of tornado-like vortices with the built structures.

Fire whirls, as compared to general fires, are characterized by significant enhancement in burning rates, flame temperature and flame heights, in addition to a strong swirling motion of the flame itself. These peculiarities allow intensifying the heat and mass transfer in different engineering devices. In a
fire whirl, the hot gases generated by the fire itself serve as a fluid sink which entrains the ambient air with angular momentum from the eddy to the vortex core (flame). Fire whirls simulation in a laboratory environment is not a new concept either. Various types of facilities may be used to produce single steady fire whirls at laboratory conditions. They are based on the concepts of generating eddy and a fluid sink. These facilities may be generally classified into two types, depending on whether the generating eddy is imposed mechanically by a rotating screen (Emmons-type or rotating screen type [10-13]) or induced by the entrained air flowing through the well-arranged spiral path (fixed-frame type [14-17]). Being similar in many aspects, since both produce a fire swirl, they differ in details.

The above mentioned experimental works dealing with the stationary whirl flows are convenient for detailed experimental description; however, their characteristics and, especially, behavior may significantly differ from the parameters of real non-stationary whirl structures, observed in Earth atmosphere.

The study of wall-free non-stationary concentrated (the vorticity is localized in space) air and fire vortices is complicated by a number of reasons, such as spontaneity of formation, space-time instability, practically impossible control over the characteristics, and so on.

This paper continues the previous investigations [18-22]. The aim of this work is an experimental study of generation of non-stationary air and fire without using mechanical swirling devices and estimation of their integral parameters.

2. The experimental setups.

2.1. The experimental setup for generation of non-stationary air whirls.

In this paper we use the simple experimental setup for controlled heating of aluminum plate top surface (here referred to as underlying surface) and for generating the wall-free non-stationary swirl structures over the plate due to unstable air stratification (the warm air near the top surface and the cold air over it). It is strictly emphasized that contrary to previous studies no mechanical swirling devices (ventilators, guide swirl vanes, screws, internal spiral ribbing, etc.) or underlying surface rotation were used for vortices generation.

The experimental setup is schematically shown in Figure 1 (left). It was located in a room with floor 1 of 6x6 m² in area and 3.3 m high ceiling 2 at a distance of 0.5 m from one of the walls 3. The experimental setup included a 0.35 m high deck 4 with three legs 5. The horizontal surface of the deck 4 was a sheet of aluminum (Grade D16AM) with a diameter of 1100 mm and thickness of 1.5 mm. The top (underlying) surface of the aluminum sheet was blackened with heat-resistant paint. The placed under the deck was an electrically ignited gas burner 6 with maximal thermal power of 3.5 kW. The diameter of flame 7 of the burner varied (for different modes of thermal power) from 200 to 300 mm. A liquefied propane-butane mixture required for the operation of the gas burner was placed in a 27-liter vessel 8. The experiments were performed in six different thermal modes, characterized by different heating times (1, 2 and 3 minutes), cooling times (10, 15 and 20 minutes) and values of maximal temperature at the underlying surface center (from 420 up 610 K). The "soft" modes (1-3) with relatively low temperatures of aluminum sheet surface were realized at low rates of heating. The "harder" modes (nos. 4-6) are characterized by higher temperatures of underlying, which are attained at high values of heat flux.

This experimental setup enables the controlled heating of the underlying surface of aluminum sheet, which leads to the generation of unsteady vortex structures 9 as a result of development of unstable air stratification. The formed vortex structures were visualized using tracer particles (micrometer-sized particles of magnesia, chemical formula 4MgCO₂Mg(OH)₂·4H₂O) or vapor of special easily-boiling fluid (VDLSL5, Velleman company, Belgium) which were applied in a thin layer onto the underlying surface prior to experiments. A digital video camera (Sanyo VCC- 6572P) was used for video filming of the generated vortices.
2.2. The experimental setup for generation of non-stationary fire whirls.

To generate concentrated vortices, we used a simple setup, the layout of which is shown in Figure 1 (right). It was arranged in a room having a floor 1 with an area of 6 m x 6 m and ceiling 2 of 3.3 m in height at a distance of 0.5 m from one of the walls 3. The experimental setup was a 0.35 m high table 4, which had three legs 5. The horizontal surface of the table 4 was an aluminum sheet (D16AM brand) with a diameter of 1100 mm and thickness of 1.5 mm. The upper (underlying) surface of the aluminum sheet was blackened with heat resistant paint. Pellets of urotropine 6 (hexamethylenetetramine, chemical formula C6H12N4) were arranged in the central part of the underlying surface before the experiment. The weight of each pellet was 21 g (40 mm in diameter). The combustion heat of urotropine is 30 MJ/kg.

Experiments were carried out with different amounts (1, 7 and 19) of the combustible pellets and different arrangements (distance between the pellets 65 and 130 mm) on the underlying surface.

In the course of the experiment, the pellets were lit forming the flames 7. During combustion of pellets, generation of fire vortices 8 was observed. Their height considerably exceeded the flame height over the fuel arrangement region. Video filming of the combustion process and generating vortex structures was performed using a digital photocamera 10 arranged on a tripod 9.

3. Results.

3.1. The conditions of generation and integral parameters of non-stationary air whirls.

The frame-by-frame analysis (see figure 2) of video records in different thermal modes provides information about the following parameters of the generation of whirls and their characteristics: (1) the values of temperature, at which the vortexes are generated; (2) the region of underlying surface, where the whirls are generated; (3) the direction of rotation of vortex structure; (4) the number of whirls observed per experiment; (5) the trajectory of travel of the vortex structure base; (6) the length of the vortex base trajectory; (7) the velocity of the vortex base; (8) the lifetime of vortex structure; (9) the height of whirls; (10) the diameter of whirls, etc.

Repeated experiments in different modes gave rise to the following inferences. A stable generation of whirls was observed in all modes except for mode no.1 [20]. Vortex structures began to form in the mode of the underlying surface heating after reaching the temperature of 470 K at its center. The largest whirls were generated at temperatures at the surface center over 570 K. Vortex structures were largely generated in a circular region of abrupt rise of temperature gradient. The direction of the
observed rotation of the majority of whirls was counterclockwise (if the underlying surface was viewed from above). Up to ten vortex structures were observed per experiment. Two types of trajectories of vortex base motion were identified. The majority of vortex structures moved in spirals (trajectories of the first type). Some vortexes moved in fact along the shortest, almost rectilinear trajectories (trajectories of the second type) from the region of their generation to the edge of underlying surface where they disintegrated.

Figure 2. The typical air whirl: (a) whirl appearance, (b), (c) and (d) whirl growth. The time between frames is 0.36 s. The visualization was made by magnesia tracer particles (mode no.6).

Figure 3. The typical air whirl: (a) whirl appearance, (b) and (c) whirl development, (d) maximal whirl development. The time between frames is 0.48 s. The visualization was made by vapor of special easily-boiling fluid (mode no.3).
The maximal length of trajectory of the vortex structures base was 50-100 cm, and the velocity was 5-10 cm/s. Therefore, the limiting lifetime of observed vortexes was about 20 s. The maximal height of generated vortex structures was 1.5 m, and their maximal diameter was 0.1 m. In the case of operation in "softer" modes (nos. 2 and 3), the number of whirls observed per experiment and their geometric dimensions were smaller (see figure 3), and the lifetime was longer than those in the case of operation in "hard" modes (nos. 4, 5, and 6).

3.2. The conditions of generation and integral parameters of non-stationary fire whirls.

The frame-by-frame analysis (see figure 4) provided information on the following parameters of the generation of flaming whirls and their integral characteristics: (1) the temporal range of the formation of flaming vortex structures, (2) the region of emergence of flaming whirls, (3) the number of observed framing whirls for one experiment, (4) the lifetime of flaming vortex structures, (5) the height of flaming whirls, and (6) the diameter of the flaming whirl.

Figure 4. The typical fire whirl: (a) maximal development, (b), (c) and (d) whirl decaying. The time between frames is 0.09 s.

Multiple repetition of the experiments allowed drawing the following conclusions. The first flame vortex structures started to form in 3 min, and the last ones, 12 min after lighting the pellets. The pellets combusted completely in 15-17 min. The flame whirls formed both in the center of the fuel arrangement and on its periphery. The number of observed whirl structures was up to 15 for one experiment. The lifetime of the overwhelming majority of generated whirls was from 1 to 5 s. The largest height of flaming vortex structures reached 0.7 m, while their maximal diameter was 0.05 m.

4. Conclusion

The generation of wall-free non-stationary air and fire whirls under laboratory conditions has been demonstrated. It is strictly emphasized that contrary to previous studies no mechanical rotation devices or underlying surface rotation were used for the whirls generation. A simple experimental facility for the generation of concentrated air and fire vortex structures by creating the unstable air stratification and solid fuel combustion (urotropine) has been described. Some data on the generation conditions and integral parameters (lifetime, height, and diameter) of air and fire whirls have been obtained.

Acknowledgements

The work was supported by the Russian Foundation for Basic Research, grant no. 18-08-01382.
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