Laser based visualization of plumes evolving from circular orifice: Effect of orifice orientation

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Abstract. The present paper is about Kelvin-Helmholtz instability and its visualization using laser-based techniques. The smoke is produced by burning an incense material which acts as a tracer. The flow field is illuminated by a pointer laser by making a laser sheet for recording the image. The images were recorded using a digital mobile camera and were used for further assessment. The flow field shows the evolution of plume from the paper cup, the formation of Kelvin-Helmholtz vortices, and its transition to turbulent flows.

1. Introduction

Fluid dynamics can be made interesting by using various flow visualization methods to study fluid flow phenomena and can also be used for various research purposes. There are various methods in flow visualization that can be used for studying flow behaviour, but in this experiment, laser-based flow visualization is carried out [1]. The experiment focuses on the theory of Kelvin-Helmholtz instability [2] where the flow from the orifice begins as a sheet of laminar flow and over some time become turbulent and loses its shape. Laminar flow which is termed as orderly and turbulent flow as Random, a flow can be determined laminar or turbulent by Reynolds number, if the Reynolds number is below 2100 it is said to be laminar and above 4000 is said to be turbulent [3]. The flow between the laminar and turbulent layer is known as the transitional layer.

The structure and physics of vortices have been studied by many researchers but among them the work of Kelvin and Helmholtz stands tall. The theory proposed by them suggests that instabilities in a flow occur when there is a difference in velocity across the interference of two fluids, these instabilities can be identified as small unstable motions occurring laterally and vertically [4]. Fluid flow tends to be laminar, as it speeds up a transition occurs, and it crinkles up into complicated, random turbulent flow. The Kelvin Helmholtz theory also predicts the transition of flow from laminar to turbulent. When the flow is in turbulent stage, the flow has eddies of all sizes moving up, as they move up, they dissipate their energy as heat. Particle image velocimetry is used to acquire the required information, A main advantage of PIV is that it is a quantitative flow field mapping technique that can provide physical insight into the overall flow behaviour [5].

Many researchers and academicians have made various experiments and analyses regarding Kelvin-Helmholtz vortices [6][7] and its behaviour in the atmosphere but this paper is distinct from others because all the materials used for the experiment were home utilities. Smoke based visualization can be used in a variety of experiments, such as flow visualisation over an Indian auto rickshaw model[8], which illustrates the use of smoke visualization inside subsonic wind tunnels, similarly smoke...
visualization can also be utilised in visualizing cylindrical bodies which is illustrated in Elementary Characterization of Smoke Tunnel using Flow over a Circular Cylinder[9]. So, this paper focuses on Kelvin-Helmholtz vortices, the time taken for laminar to turbulent transition, and flow behaviour when the orifice is made in two different regions of two paper cups.

2. Methodology
The methodology here is to perform the smoke based visualization [10] experiments by placing an incense material inside two different inverted cups in which one has an orifice on the top and the other on the side of the paper cup from which a thermal plume is ejected. The smoke emitted by the incense material has a temperature higher than the ambient temperature and the smoke ejected has a lower density than its surroundings, so it rises and according to Kelvin-Helmholtz instability vortices are created and after some time the flow becomes turbulent. The vortices are visualized using a green laser fixed to the glass rod to create a laser sheet. The laser sheet is aligned parallel to the axis of the orifice in the paper cup.

3. Materials required
The materials used in this experiment are two paper cups, with different orifice positions, a green pointer laser, a glass rod, a laser stand, black paint coated cardboard sheets, and a digital mobile camera. figure 1 shows the complete experimental setup and the paper cup with orifice present on its face [11].

![Figure 1. A schematic showing experimental setup and items used for performing the experiment.](image1)

![Figure 2. Top view of paper cup having orifice on the top.](image2)

Figure 2. is the top view diagram of the paper cup with orifice position on the top, the experimental setup is not changed and only the paper cups are changed.
4. Experimental setup
Figure 2 below shows the experimental setup made at home during the COVID lockdown with basic home utilities. The setup is placed on a steel base and it is surrounded by a black background made using cardboard piece. An incense material placed inside an inverted paper cup produces smoke out of a 1cm diameter orifice which is used as a seeder [12]. A green pointer laser of wavelength 532nm is attached to a glass rod of 0.8cm diameter which creates a laser sheet that shined parallel to the orifice. The laser-glass rod set up is placed at a height of 51cm from the paper cup. The camera is placed 35 cm from the inverted paper cup. The experiment was performed with no external flow disturbances.

Figure 3. Photograph showing the experimental setup made at home.
5. Results and Discussion

Figure 4. Comparison of thermal plume ejection from two orifice positions in paper cups.
Figure 5. Comparison of thermal plume ejection from two orifice positions in paper cups.
5.1. Side Orifice SO (a to j)
SO in figure 4 and figure 5 stands for Side Orifice, observing the pictures from SO(a to j) we can understand the flow transition from laminar to turbulent from an orifice placed on the face of a paper cup, we can also understand the gradual separation of the thermal plume and also study the vortices formed during the turbulent stage of the flow.
SO(a) shows the initial flow coming out of the Side Orifice. At first, the flow is slow and tends to be laminar, at a certain height due to instabilities vortices are formed and the flow becomes turbulent and the initial vortex stage is seen in this picture. SO(b) to SO(f) shows how the initial vortex has further developed into larger eddies. In SO(g) and SO(h) the large eddies formed are partially separated from the flow and in SO(i) and SO(j) the eddies were completely separated and becomes completely turbulent.

5.2. Top Orifice TO (a to j)
TO in figure 4 and figure 5 stands for Top Orifice. Pictures TO (a to j) shows the flow of thermal plume and its transition from laminar to turbulent flow, we can also study the structure of Kelvin Helmholtz vortices and their separation from the thermal plume.
TO(a) shows the initial flow coming out of the Side Orifice. In TO(b), at a certain height due to instabilities vortices are formed and the flow becomes turbulent and the initial vortex stage is seen. TO(b) to TO(g) shows how the initial vortex has further developed into larger eddies. In TO(g) and TO(i) the large eddies are formed and starts to partially separate from the flow and in TO(i) and TO(j) the eddies gets completely separated and becomes completely turbulent.

5.3. Observation
From figure 4 and 5, the vortex formation starts in SO at SO(a) and in TO at TO(a), as they progress further, the small vortices begin to evolve into larger eddies, this can be seen in SO from SO(b) to SO(g), it can be seen in TO from TO(c) to TO(h), by looking into the time comparison between SO an TO, there is a delay in formation of primary vortices on TO compared to SO, as a result of that the transition from laminar to turbulent occurs faster in SO than TO. The complete turbulent transition occurs at(7/60s) in SO and at (8/60s) in TO, after these stages, the flow dissipates its energy into heat into the atmosphere.

6. Conclusion
Comparing SO and TO, the transition of laminar to turbulent flow occurs earlier in SO whereas the transition in TO takes time compared to SO. From the above information, it can be learned that the orifice orientation influences flow separation at various intervals.

7. Reference
[1] https://sites.google.com/view/drbtk/courses/ [website accessed on 18th august 2020].
[2] Kelvin-Helmholtz instability:
http://hmf.enseeih.fr/travaux/CD0001/travaux/optmfr/hid0pa/hyb72/kh/kh_theo.htm.
[Accessed on 18th August 2020]
[3] White F M (1999). Fluid mechanics. page 307 8th edition, Boston, Mass: WCB/McGraw-Hill.[ book accessed on 18th August 2020]
[4] Thakkar K, Kesarwani A, Khan A, Sunil R, Malhotra V and Kannan B T, 2019, "Experimental Investigation on Laser Visualization of Flow Vortices," IEEE Aerospace Conference, Big Sky, MT, USA, pp. 1-11, doi: 10.1109/AERO.2019.8742103.
[5] Atkins M D, 2016 Velocity Field Measurement Using Particle Image Velocimetry (PIV) in Application of Thermo-Fluidic Measurement Techniques, https://doi.org/10.1016/B978-0-12-809731-1.00005-8
[6] Thorpe S 2012, On the Kelvin–Helmholtz route to turbulence. Journal of Fluid Mechanics, 708, p 1-4. doi:10.1017/jfm.2012.383
[7] Bentata O, Anne-Archard D and Brancher P, 2018 Experimental study of low inertia vortex Rings in shear-thinning fluids: Physics of Fluids 30, 113103); doi:10.1063/1.5048841
[8] Saransh Abbey, Pratyush Kumar Singh, Neha Singh, KANNAN B T, 2020, Flow Visualization over an Indian Autorickshaw Model, IOP Conf. Ser.: Mater. Sci. Eng., 912, 022004
[9] Keerthana K, KANNAN B T, 2020, Elementary Characterization of Smoke Tunnel using Flow over a Circular Cylinder, IOP Conf. Ser.: Mater. Sci. Eng., 912, 042018
[10] Akash Balachander, Akash Alase, Aditya Menon K, Mahendra Perumal G, KANNAN B T, 2020, Smoke based Visualization of Turbulent Swirl Jet Flow, IOP Conf. Ser.: Mater. Sci. Eng. 912 022011
[11] Naresh Kumar M, Sri Vijay Prabhu R, Gousik R, KANNAN B T, 2020, Design and Development of Low-Cost Fluidized Bed Seeding Generator, IOP Conf. Ser.: Mater. Sci. Eng., 912, 022005
[12] Abdul Hamid Rather, KANNAN B T, 2020, Design and Development of Impinging Jet Facility for Flow Visualization Studies, IOP Conf. Ser.: Mater. Sci. Eng. 912, 042003