Design and development of impinging jet facility for flow visualization studies

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Abstract. Smoke flow visualization is employed to investigate the behavior of a round jet issuing from a straight tube and impinging on a flat plate or bodies mounted on a support. Smoke jet impingement facility is a tool used in aerodynamic research to provide information about the behavior of a round jet of smoke impinging on a model. The smoke impingement jet facility utilizes smoke as seeding for scattering towards visualization. In this study, an impingement jet facility is designed and fabricated that ought to be of low price and straightforward to use. This project aims to offer educators and students an economical means to demonstrate flow impingement over completely different objects employing an easy variety of construction. This work utilizes a smoke generator that can produce good quality smoke and have sufficient density to be visible. The application of this smoke jet impingement jet facility over several test visualization techniques is that it produces high-quality visualizations. The facility has proven to be an economic addition in supporting other research projects and is anticipated to be a valuable ‘hands-on’ addition to existing aerospace laboratory teaching.

1. Introduction
Wind tunnels are excellent tools that help us to understand the phenomenon associated with aerodynamics. Wind tunnel experimentation helps us to understand various concepts that are linked to the aerodynamic structures. It is also used to understand the behavior of an aerodynamic body in a moving condition. With the help of wind tunnel, parameters like lift and drag on various structures can be estimated. The new aerodynamic structures are subjected to tests before they are been used in real applications. Construction may be a tool utilized to design new things in every field to check the consequences of one thing over the other like the construction of an impingement tunnel where flow over a solid object can be analyzed. Construction consists of a can-annular passage with the item at the end of the nozzle on which fluid is injected to study the behavior of a fluid.

The smoke impingement tunnel can be used as smoke-producing equipment for the subsonic wind tunnel. This smoke tunnel can also be used for the same if the part pipe facing downwards is removed and we can face that opening into the subsonic wind tunnel. On the other hand, it can be used as a simple horizontal smoke tunnel by the same procedure as above. The only thing which is to be designed is a test section in which aerodynamic bodies can be placed. Due to these ways, this smoke impingement tunnel can be used in different ways.

From early times, fluid dynamics has been an important field which helps us to understand the various phenomenon. This field has been studied on a large scale but there are still some aspects that have to be investigated [1]. Flows have been studied to understand the behavior of fluids over various...
vehicles. These studies lead to the development of vehicles and the design of mechanical parts. The automobiles, aircraft and the mechanical parts of such vehicles are developed using these studies of fluid flows. The studies help us to know the flow dynamics over these vehicles. These tests are useful to develop a performance efficient vehicle. Wind tunnels, which help us to study these flows are designed and developed based on various calculations. The parts which make up wind tunnel are designed in such a way that the parts improve the quality of flow. The parts which are used in the wind tunnel and the features of such parts are studied by [2]. They illustrated the working and features of parts of the wind tunnel. There are different types of wind tunnels that are used to study the flow past different objects according to their design. The open-circuit wind tunnel is of the type in which the flow is drawn from and to the atmosphere. The design and construction of such a wind tunnel were done by [3]. They studied discussed the design and types of wind tunnel. This study carried out the testing in which they used a Pitot tube, manometer. The other type of wind tunnel is a closed-circuit wind tunnel in which the same fluid is used for testing. The fluid which is exhausted is drawn back to the inlet. These tunnels are comparatively larger than the open-circuit wind tunnels and are complicated to design. The design, construction of such a wind tunnel was done by [4] and also, they carried out the testing for laminar and turbulent flow.

Flow impingement is one of the fields of fluid flow dynamics in which the flow of high velocity is allowed to pass through a slit or hole. The flow is then allowed to impinge on a surface at different conditions. Flow Impingement has a wide range of applications aerospace field which include cooling of gas turbines, combustion chamber. Also, flow impingement is used in the cooling of printed circuit boards, microelectronic components. The Laser Visualization of Flow Vortices was studied experimentally by [5]. An experimental study was done on the distribution of effectiveness on a flat plate by [6]. This study helped in studying experimentally the distribution of Nusselt number along with the distribution of effectiveness on a flat plate using an impinging jet of rectangular cross-section. A numerical study has been done using the Spalart-Allmaras turbulence model by [7] in which they studied the flow and heat transfer characteristics of impinging cooling. Another study carried out to analyze the flow and heat transfer characteristics of a single jet [8]. They studied the single jet impinging over the dimpled surface experimentally and numerically.

The flow visualization is the tool used to study the dynamics of flow over the wide range of objects using by injecting the smoke into the air. The smoke used should be non-toxic and should have a low mixing rate with the air. The smoke is produced in different ways by different substances. Smoke flow visualization reveals the flow pattern around the objects. The smoke flow visualization is done by designing a whole new wind tunnel for this purpose. Also, smoke flow visualization is done by developing a system for wind tunnel [9]. This study developed a smoke visualization system for vertical wind tunnel and they used fog machines for smoke generation. Smoke visualization is done also by incorporating smoke lines into the test section which provides good quality visualization. The wind tunnel can be converted into a smoke tunnel [10] using smoke wire. This study improved the quality of flow by modifying the settling chamber. There are various methods for a visualization based upon the medium in which visualization is to be done [11]. One method uses smoke, dye, fog to carry out the visualization. Other methods include dye production, hydrogen bubbles, use of tuffs, liquid crystals, oil and pressure, and temperature-sensitive paints. These methods are used according to medium visualization takes place.

Flow visualization is of utmost importance in various applications like cooling and combustion. It also reveals the parameters which affect the flow over objects. The study was carried out by [12] in which the numerical investigation carried out by considering the two cases in which the effect of geometric parameters on axisymmetric jet impingement heat transfer was examined. The study was conducted on the flow dynamics of a single round jet impinging on a porous medium [13]. This study used smoke wire flow visualization and studied the factors like Reynolds number, the permeability of the porous medium. Flow visualization of round jet impinging on the cylindrical surface [14] was done by studying the effect of nozzle diameter, Reynolds number, nozzle to surface distance and Relative curvature on the flow. The flow over different shapes has always pawed the way to understand the
flow dynamics over objects having these shapes. The study of laminar impinging flow upon convex cylinder [15] was studied by varying the parameters like a cylinder to jet diameter ratio by keeping the jet to cylinder separation the same.

This study focuses on designing and fabrication of an impinging jet facility with an adjustable test section designed to study fluid flow over different bodies. This is done by using material that is easily available in the market. The facility is designed in such a way to meet the requirements of a wind tunnel. The facility is held up in a vertical position by a steel stand. The height of this facility is 5 feet. The most important part of the design is the test section. The dimensions of the test section are 2 * 1.5 feet. The test section is high enough to facilitate the study of a wide range of objects. This facility is also used as a smoke-producing source for subsonic wind tunnel (SWT) when the nozzle is directed in the subsonic test section and smoke tunnel. This facility has the advantages over others as the flow over objects can be studied in a vertical and horizontal position.

The construction of jet impingement setup to carry out the experiments has many advantages. The availability of this facility will help the students to do experiments and learn the fluid flow over the wide range of objects. This facility added a feature to the existing Aerodynamics laboratory of the aerospace department. Figure 1 illustrates the structure of the aerospace aerodynamics department laboratory.

![Figure 1. Structure of the Aerospace Laboratories.](image)

2. Overall Design of Smoke Tunnel
For the convenient manufacture and smooth experimentation, the cross-section of the smoke impingement tunnel is designed cylindrical. From air inlet to air outlet, the structure of the wind tunnel is circular. Inlet, honeycomb, contraction sections and outlet are shown in figure 2. The parts of the facility are labeled individually for easy understanding.
The main aim of this study is to construct a jet impingement facility for flow visualization and the flow dynamics of impinging jets at different Reynolds numbers. The Reynolds number ranges from 500 to 3500. This jet impingement Facility was constructed from commercially available things. The smoke impingement tunnel was designed from the things listed below in table 1.

![Figure 2. Cross Section of jet Impingement Facility.](image)

| Materials            | Use                                      |
|----------------------|------------------------------------------|
| PVC Pipe             | Main Body of the Impingement Jet Facility|
| Steel Mesh           | Used as Screens                          |
| Compression Adapters | Design the Compression Part              |
| Coupling             | Join the Separated Parts                 |
| Blower Fan           | Fluid Drawing Unit                       |
| Plywood              | Used in Test Section                     |
| Digital Wireless Regulator | To Control the Speed of Fan             |
2.1. Design and Fabrication

The jet impingement facility was designed meeting condition which is important for designing wind tunnel on a small scale. The facility is given the circular cross-section of a suitable diameter. The PVC pipe used is 152.4mm in diameter which is divided into 4 parts each connected with the coupling. While connecting the two parts, the mesh is placed in between them (figure 3).

![Figure 3. Divisions of Smoke Impingement Tunnel.](image)

The wire meshes (also called gauzes or screens) are a very important part of any wind tunnel. The screens used in this jet facility have a fine size and are made of steel. The screens used in wind tunnels are made from different substances like metal, plastics. The screens are used in this facility to convert the turbulent disturbances into smaller ones. Also, screens help in minimizing the fluctuations in the flow. The facility is given 4 meshes made of steel, one being in front of the fan to avoid dirt to enter into the tunnel (figure 4). The Screens are placed in a manner to get the less turbulence flow in the test section.

Honeycombs are another important part which aligns the flow parallel to the walls of the facility and remove the unsteadiness in the flow created by a fan. The effect of honeycomb is to minimize the unsteadiness, which also is done by screens. The honeycomb in the present tunnel is made from straws of length 100mm and of diameter 4mm. the honeycomb is present adjacent to the blower fan reducing turbulence and fluctuations in flow (figure 5).

![Figure 4. Mesh of Size 1mm.](image)  ![Figure 5. Honeycomb.](image)
The fan used in this smoke impingement tunnel is a 3-blade axial fan with a tilting angle of 20 degrees, 150mm sweep and 2400rpm. It is made of plastic which needs an operational current of 0.57A and power consumption of 30 W (figure 6).

The fan is connected to a digital wireless remote fan regulator with 9 step speed control which can be controlled in a range of 30ft. Wireless fan regulator allows us to vary the speed of the fan and analyze the flow at various speeds (figure 7).

2.2. Design of contraction part of Smoke impingement Tunnel
The settling chamber having a diameter of 6 inches of the jet impingement facility is connected to the compression adapter which has an exit diameter of 4 inches. The contraction part accelerates the flow and aligns it to the test section. The design of the contraction part determines the flow quality in the test section. The contraction part is designed according to the desired parameters which do not affect the flow steadiness. The contraction part is given with a circular cross-section to avoid the corner flow separation.
2.3. **Final Assembly**  
The whole assembly is kept in a vertical position by a stand which is 2feet*2feet and has the height of 4 feet. The assembly is fitted at one corner (figure 9). The remaining top surface of the stand is equipped with a test section which is made from plywood and is closed on 5 sides to block any disturbance from outside to the flow issued from the nozzle. The whole assembly is shown in figure 10.
3. Experimental methodology
The smoke visualization experiments can be carried out using several methods. The material which is used to produce smoke is many like dry ice, kerosene, dung, etc. which are burnt to produce smoke. Some of the materials used for smoke production are listed in table 2. However, the materials which produce harmful smoke and are hazardous to the environment are not used. The smoke used in this facility to carry out the visualization experiments is incense material which is non-toxic and is used in small quantities. The incense material is also economic and harmless.
The test section in which the actual visualization takes place is made using plywood coated with a white covering. The plywood boards were set up using clamps. The base and back section was made from plywood. The two plywood boards were set up using the clamps. The nylon mesh was used to cover the other sides of the test section is harmless with regards to inquiries to skin. The test section is covered with this mesh to give free ways to smoke to flow out of the test section. On the right side of the test section, the nylon mesh was given with the cut to allow the laser sheet to pass through without any blockage or discontinuity. The test section is 2 feet in length, 1.5 feet in breadth and height (figure 10).
Table 2. Smoke Producing Materials.

| Materials            | Advantages                      | Disadvantages                  |
|----------------------|---------------------------------|---------------------------------|
| Tobacco, Kerosene    | On burning Produces high-quality smoke | Hazardous to Environment and Health |
| Carbon Dioxide       | On Burning Produces Dense Smoke | Harmful                         |
| Water-Based Liquids  | On burning Produces Dense Vapours | Internal Disturbances Due to Vapour Condensation |

3.1. Test section Illumination and Image Capture
For good visualization results and flow analysis, it is necessary to sufficiently illuminate the smoke issuing from the nozzle. The illumination of the test section is important to record the visualization. For illumination, a green laser of 532nm is passed through a cylindrical lens to produce a laser sheet. The laser sheet is allowed to pass through the nylon mesh and illuminate the area of interest. The camera for image capture was placed directly in front of the test section on a rectangular piece of plywood which is connected to the iron stand. The camera used in the present work is a simple phone camera.

3.2. Test conditions
The jet impingement facility was operated and tested at various Reynolds numbers to analyze the flow behavior issuing from the nozzle with high-quality smoke visualization. The nozzle diameter was also changed for testing the facility.

4. Results and discussion
In this section, the images taken from the visualization experiments are discussed briefly. The Reynolds number was increased from 500 to 3500 and the behavior of the impinging jet was seen. The effect of Reynolds number on the impinging jet issuing from a nozzle of the diameter of 11.2 mm is discussed.

4.1. Flow Dynamics of Impinging jet at various Reynolds number
In this study, the dynamics of the impinging jet are studied briefly by varying the Reynolds number. This study presents significantly small Reynolds number and round jet through which smoke jet is issued. The jet impinges on a flat surface in a stationary air surrounding. The distance between the jet nozzle and the flat plate is kept 50.5mm. The jet issued from the nozzle is studied before it hits the flat plate as a testing experiment for the facility. The Reynolds number is varied from 500 to 3500. The jet is issued through a nozzle having the diameter 11.2mm at various Reynolds numbers. The jet issued from the nozzle is studied at \(Re= 560, 1200, 2600, 3400\) keeping the nozzle diameter and distance of separation between flat plate and nozzle the same. The results show the change in jet flow when the Reynolds number is increased.

The toroidal vortices are formed in the shear layer of an impinging jet before hitting the flat surface. When these vortices reach the impinging surface, the follow the path of jet flow and move out radially from the stagnation point [15].

The initiation of the vortex is identified by tracking down the first instability in the laminar shear layer. The result of these instabilities is the formation of vortices. The vortices roll down along the
wall jet if the distance of separation between nozzle exit and stagnation point is small. If the distance of separation is large then the vortices roll up into the ambient air. The vortices are formed near the flat surface at Reynolds number 700. The initiation of instabilities can be reviewed by looking at the video recording. In figure 11, no instabilities are found in the jet flow before impinging on the flat surface. The vortices are found in wall jet yet the vortices are not found before the impingement.

At low Reynolds number, the jet flow is steady without any instabilities as can be seen in figure 11. The jet flow is seen to have a laminar flow pattern. As the Reynolds number is increased, the changes can be seen at the lower part of the jet as shown in figure 12. The disturbances start to appear because of the transfer of momentum laterally outwards, which pulls the additional air along the jet which increases mass flow. The instability in the shear layer increases and the jet flow has these instabilities just before it hits the flat plate (see figure 12). The increase of Reynolds number changes the jet flow from laminar to disturbed flow having many instabilities. The jet loses energy due to an increase in Reynolds number and the widening of the velocity profile happens. When the flow reaches the flat plate flow experiences high shear stresses in the less accelerated region, due to this the local transport property of the jet is influenced greatly. The resulting jet flow generates the vortices in the flow and disturbance increases. The instabilities appear in the jet flow just after leaving the nozzle resulting in unsteady jet flow (figure 13 & 14).

4.2. Visualization Results

![Figure 11. Re = 560.](image-url)
Figure 12. $Re = 1200$.

Figure 13. $Re = 2600$.

Figure 14. $Re = 3400$. 
5. Budget
The cost which was used to build this setup of smoke impingement tunnel is slightly lesser than Rs.5000. The items which were bought for this setup were brought from local stores that are easily available in these stores and are listed below.

| Materials             | Uses |
|-----------------------|------|
| PVC Pipe              | 1500 |
| Honeycomb             | 100  |
| Steel Mesh            | 200  |
| Fan                   | 1110 |
| Hardware              | 400  |
| Digital Wireless Regulator | 1100 |
| Others                | 500  |
| **Total**             | **4910** |

6. Conclusion
A jet impingement facility for smoke flow visualization in a university has been designed and constructed successfully. This facility was fabricated using easily available material in the market. The design of this facility was simple and it took a small effort to construct. The cost which was used to manufacture the facility is less than Rs5000. This facility has proved to be the best alternative to the large-scale jet impingement tunnel which costs many folds than this facility. The experiments were carried out to test the facility of which the results were good. One experiment was carried out to analyze the dynamics of jet flow at different Reynolds number which is listed above. The study of dynamics of jet flow at different Reynolds numbers showed that the jet flow is affected by the Reynolds number. At low Reynolds number, the flow was laminar which then changed to disturbed flow due to an increase in Reynolds number. The facility is currently used in students for their major project works by carrying out the experiments easily. This facility has also added to the aerospace laboratory at the university.

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