Design and analysis of smoke flow visualization apparatus for wind tunnel

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Abstract. In the present study, the design and analysis of smoke generator are done for the low-speed wind tunnel. The wind tunnel fan is fitted with the Variable Frequency Drive to produce the wind speed in the range of 3 to 32 m/s with fan speed of 150 to 1500 rpm. The design of smoke generator was done according to Preston Sweeting mist generator principle corresponding to the free stream velocity of 3 m/s. A controlled smoke generator consisting of kerosene reservoir, controlled heater, blower, liquid column height adjustment mechanism, valves etc. was designed and fabricated. The smoke generator produced the smoke at the rate of 154 cm³/s which was close to the design flow rate of 149 cm³/s. To supply the required quantity of smoke in the wind tunnel, the smoke rake of NACA 0010 profile was developed and installed in the rapid contraction section of the wind tunnel to achieve the streamlined flow. The parametric studies were done on the smoke generator at different power inputs and its effects were studied on smoke temperature, smoke discharge and boiling time of the kerosene. The flow visualization was carried out on NACA 0015 airfoil model and the images were captured to examine the flow physics around them under different operating conditions.

Keywords: Design, NACA, smoke generator, flow visualization, wind tunnel.

1. Introduction

The smoke flow visualization system is one of the ways to visualize the air flow in the wind tunnel. The need for the smoke visualization technique is necessary to understand that how the flow behaves around or over the body. It gives the idea of the major design procedure of any machine or any corrections needed in the design. Many techniques are available for the flow visualization for the wind tunnel. Be it smoke visualization, tufts, china clay visualization etc. [1]. The smoke visualization is considered appropriate for better understanding of the flow over the object. The smoke flow visualization can be achieved by various means. The technique depends on the type of the visualization and also on the cost procurement of the project. Basically, oil smoke visualization is preferred in the low-speed subsonic wind tunnels, as at the low speeds of around 2 to 3 m/s [1], the smoke does not diffuse in the tunnel and travels with the air in it.

The most important aspect of flow visualization is the condensation, due to which the smoke becomes visible to naked eyes. Usually, the size of the smoke particles is around 0.3 to 0.5 micron. The condensation process plays major role in the flow visualization system. Also, other factors such as
density, luminosity etc. play key role for the proper smoke discharge. Also, the smoke particles should be appropriate to control the settling velocity of smoke. The sizes of the smoke particle generated from different sources differ and also depends on the heating instrument used in it. Usually, low particle size results in low settling velocities and large particles results in higher settling velocities. The particle size should be kept small so as to prevent the solid deposition in the flow field [2].

2. Development of smoke rake

The smoke rake is a hollow airfoil shaped component, with the hollow tubes attached at its trailing edge from which smoke is ejected. For the design of smoke rake, NACA airfoil profile is selected which is a symmetrical airfoil. The chord length of the airfoil is selected as 127 mm, as with the increasing chord length the thickness of the airfoil would also increase resulting in the flow separation in the wind tunnel. For the design of the smoke rake, the design parameters considered are (i) the smoke rake must maintain its proper airfoil shape and must free from any dents on the surface (ii) the tubes attached at its end must be properly aligned with the shape of the smoke rake.

Based on the chord length of the NACA 0010 airfoil, the design of the smoke rake was done based on the cross section of the contraction cone of the wind tunnel. The smoke rake has to be installed at the rapid converging section of the wind tunnel where the air flow would accelerate over the symmetric smoke rake such avoiding the adverse pressure gradients and as a result the smoke would travel with the air smoothly without any disturbances. The smoke rake has been installed at the distance of 15" from the test section to the contraction cone. The height of the smoke rake is kept as 14.60". The smoke rake is manufactured from stainless steel because of its high strength and could also withstand high temperatures. The smoke rake is shown in the figure 1.

The fuel used to produce smoke is taken as kerosene because of its easy availability and less toxicity as compared to other fuels. The total volume of the smoke is calculated based on the free stream velocity of 3 m/s. Based on the requirement of smoke for 30 minutes, 2 liters of kerosene capacity is required. Experimental work is also undertaken for the estimation of the smoke discharge time from the fixed amount of the fuel. The smoke rake is installed at the specified junction in the contraction cone, so that the smoke would easily travel with the air flow in the tunnel.

3. Design of smoke generator

3.1 Design principle

In the present study, the smoke generator is designed based on the principle of Preston Sweeting mist generator [1]. Figure 2 shows the schematic diagram of the smoke generator based on this principle. The working of the Preston-Sweeting mist generator is as follows.

- The kerosene is filled in the boiler glass tube which is connected to the kerosene reservoir via U-tube connection.
- A spiral heater is wound around the glass tube, which supplies heat to the glass tube and eventually boils the kerosene.
- The vapor from the kerosene travels through the jet in the mixing chamber where it mixes with the cold air to be supplied by the fan.
- As the hot vapor of kerosene mixes with the air, it condenses and forms the dense white smoke.
- This smoke is guided by the outlet pipe to the separator where it is stored.
- This stored smoke is then released in the wind tunnel through the valve mechanism.
- During the boiling of kerosene no heat loss is taking place.
- The velocity of smoke in the smoke rake is same as the free stream velocity in the wind tunnel.
3.2 Design of smoke generator

The design of smoke generator was carried out corresponding to free stream velocity of 3 m/s at the wind tunnel fan speed of 150 rpm. At the speeds higher than 5 m/s to 8 m/s the smoke would diffuse and would result in the failure of the flow visualization [3]. For the installation of the smoke generator in the wind tunnel system, usually the smoke generator is installed at the test section entry so that the smoke gets easily aligned with the flow. But the problem with the installation of the smoke generator at the entry of the test section is that, the flow will not develop and streamlined flow will not be obtained. Hence it is better that it should be installed at the low-pressure section of the wind tunnel. The contraction cone at which the section rapidly converges is the appropriate place for the placing of smoke rake which would supply the smoke from smoke generator. Figure 1 shows the smoke rake. In the smoke rake, 7 cylindrical tubes will be provided with ID and OD of 3 mm and 4 mm respectively with the length of 10 cm. The cross section of a tube was determined as follow:

\[
A = \frac{\pi}{4} \times d_i^2
\]  

(1)

Based on the smoke rake to be installed in the wind tunnel the volume of the smoke to be used is calculated as:

\[
Q = A \times v
\]  

(2)

where, \(Q\) = smoke volume discharge for one pipe, \(A\) = Cross sectional area of tube, \(v\) = Velocity of 3 m/s.

Hence, such 7 cylinders would contribute to about 148.45 cm³/s of smoke. Also, the experiment was conducted for about 30 minutes and hence the total volume of the smoke required was 267210 cm³. Now in order to match the desired smoke volume, the fuel capacity has to be calculated. So, the mass of the smoke can be calculated by multiplying its vapor density with the total volume. Hence the mass of the smoke is calculated as follows:

\[
Mass\ of\ smoke = Total\ volume\ of\ smoke \times vapor\ density
\]  

(3)

Now an assumption is to be done that, no evaporation loss is taking place. Hence the amount of the liquid kerosene evaporated is equal to the amount of smoke generated. As only phase change takes place and mass remains constant, the volume of the kerosene can be found by:

\[
Volume\ of\ kerosene = Mass\ of\ smoke/Density\ kerosene
\]  

(4)

Hence, for the production of the required amount of smoke, 2 liters capacity of kerosene is needed. The time duration for which the smoke will be liberated from the kerosene for a fixed mass is decided.
by conducting a small-scale experiment. The smoke rake will be made of symmetric airfoil shaped tube which will be inserted in the direction of flow in the wind tunnel. Small tubes will be inserted at its trailing section of the smoke rake from which the smoke will be discharged. It was installed at the converging section of the wind tunnel because the pressure will constantly reduce that helps the smoke travel through the tube without any disturbance.

4. Development of smoke generator

As discussed earlier, the smoke generator is designed based on the principle of Preston Sweeting Mist generator. Figures 3 and 4 show the smoke generator setup and the wind tunnel developed at Nirma University. The glass tube is subjected to the external heater with the rock wool insulation in order to minimize the heat losses. Flow control valves are also installed in order to control the air flow in the mixing chamber to produce the required amount of smoke. The high temperature resistant silicon tubes are used for supplying the hot vapors and kerosene to the mixing chamber and glass tube. A drain vessel is provided for collecting the condensed kerosene which can be used again. Table 1 shows the major specifications of the smoke generator.

![Figure 3. Smoke generator](image-url)
5. Result and discussion

5.1 Flow visualization around an airfoil

The flow visualization is an important aspect of examining the flow physics around the various objects. In the present study, the flow visualization is carried out around NACA 0015 airfoil at different time intervals as shown in Figure 5 [4].

![Flow visualization near airfoil at different time](image-url)

**Figure 5.** Flow visualization near airfoil at different time
Parametric study

In the present study, to evaluate the performance of smoke generator parametric studies were done. The effects of boiling time of kerosene, smoke temperature and smoke discharge were studied by varying the power rating at various flow speeds in the mixing chamber. Experimental analysis was carried out in order to measure the smoke temperature and an estimated smoke discharge from the smoke generator. For the experimental purpose (i) a fixed amount of kerosene was taken i.e. 77 ml (ii) valve positions for the air flow were fixed at two points, correspond to the air velocity in the mixing chamber as 4.8 m/s and 7.2 m/s (iii) same amount of kerosene was subjected to different power inputs in order to estimate the smoke temperature and smoke discharge (iv) kerosene boiling time was noted, in order to match the design criteria of boiling the kerosene in 5 minutes.

Figure 6 shows the smoke temperature for same amount of kerosene at different power inputs. It can be seen that at the same power rating, the smoke temperature differs with the air velocity. This is because, at higher flow speeds, the hot liquid rapidly condenses and also gets carried away with the flow resulting in the less smoke temperature. By decreasing the air flow, the smoke temperature increases with increased amount of smoke rate. Further decreasing the air flow results in abnormal smoke generation, which would not allow the smoke to eject out of the glass tube.

Figure 7 shows the estimated smoke discharge from the smoke generator at different power inputs [4]. It can be observed that at lower air speeds the smoke discharge increases as compared to the air flow subjected to higher speeds. Because at the higher air flow rates, the hot vapors condenses rapidly producing less amount of smoke. The smoke generator should not be operated at higher speeds, as the hot liquid particles gets carried away with the flow and damages the equipment. The trend shows that, that at 4.8 m/s velocity and at 550 W, the smoke discharge matches its approximate design criteria of 148 cm³/s. The kerosene boiling time is predicted based on the power inputs. Figure 8 shows the trend of the kerosene boiling time with variation in power input. The design criteria are based on the maximum 5 minutes boiling time of kerosene.
6. Conclusions
In the present study, the design of smoke generator is done according to Preston Sweeting mist generator principle corresponding to the free stream velocity in the wind tunnel as 3 m/s. The parametric studies were done on the smoke generator at different power inputs and its effects were studied on smoke parameters. The smoke generator has produced the smoke at the rate of 154 cm³/s which was very close to the design flow rate of 149 cm³/s. The smoke rake was installed at the rapid contraction section of the wind tunnel to avoid the flow diffusion and it led to streamlined flow. When power input was varied from 32 W to 626 W, the smoke temperature, smoke discharge and boiling time were changed in the range of 37° to 76°C, 61 to 154 cm³/s and 45 to 3 minutes, respectively at an air velocity of 4.8 m/s in the mixing chamber. The flow visualization was carried out on NACA 0015 airfoil model and the images were captured to examine the flow physics around them under different operating conditions.

7. References
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