Flow pattern generated by a radial jet

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Abstract

The article is focused on a radial jet investigation. The radial jet is one of the most important features of a reinforced exhaust system known as the Aaberg exhaust hood. In order to describe a radial jet flow pattern, measurements of radial jet characteristics, such as velocity decay, spreading rate and turbulence intensity profiles across the jet, are needed. An experimental set-up has been built up. It allows the measurements to be taken under various geometrical (jet width and orifice diameter) and initial conditions (turbulence intensity, air speed, and temperature at the inlet).

The set-up consists of an air terminal that creates the radial jet, a ductwork with a fan unit and a heat exchanger. The basic dimensions of the air terminal are 200 mm in diameter and the width of the terminal nozzle is 4 mm; both of them are adjustable. The flow rate can be varied from 50 to 1200 m^3/h. Data acquisition system is based on a computer and it enables the storage and evaluation of data from all measuring devices and sensors in real time. For the basic arrangement, a set of measurements were undertaken and results of that were compared with available literature. The radial jet was also simulated numerically by means of a commercial CFD code with the aim of using this tool for further development and optimisation of radial jet reinforced exhaust system. Comparison of the results, both experimental and numerical, with available expressions and data for velocity decay shows as much as 30 % discrepancy.

Introduction

During research in the field of local exhaust systems, the Aaberg exhaust hood in particular, importance to model radial jet correctly has appeared as the modelling is intended to be applied to further investigation and optimisation of the system. The radial jet is one of the most important features of a reinforced exhaust system; a system that makes use of the jet in order to achieve perform favourably when compared with a traditional exhaust hood. The effect of the jet on a flow pattern in front of the exhaust hood is multiple. It creates a virtual wall so the suction takes place in hemisphere only which is makes the suction more efficient as the positive effect of a flange has been shown by many authors, e.g. Fletcher [1]. Another phenomenon associated with the jet is that the jet entrains the fluid that surrounds it so it moves towards it. In this way a directional flow pattern is created. Although the radial jet may seem to be well documented [2], [3], the data available is not sufficient for validation of the modelling.

Experiments

Should the radial jet be modelled and the model validated, measurements of a radial jet characteristics, such as velocity decay, spreading rate and turbulence intensity profiles across the jet, are needed. An experimental device has been built up. It allows to perform the measurements under various geometrical (jet width and orifice diameter) and initial conditions (turbulence intensity, air speed, and temperature at the inlet).

The main part of the experimental set-up is a testing room (size 5.5 × 5.5 × 5 m) where a device for generation of a radial jet is situated. The experimental device consists of an air terminal depicted in Figure 1 that creates the radial jet, a ductwork with a fan unit and a heat exchanger [4]. The basic dimensions of the air terminal are 200 mm in diameter (flange and disc) and the width of terminal slot is 4 mm; both of them are adjustable. The equipment of the testing room allows us to obtain experimental data for exact description of a radial jet. The remote controlled fan unit allows us to control flow rate through air terminal in range from 50 to 1200 m^3/h. In order to account for the initial conditions of the radial jet at the jet origin (supply slot), measurements of pressure, temperature and flow rate of supplied air are conducted.

Output signals from all devices and sensors are processed by a computer measurement system that is based on distributed input/output ADAM modules. Measuring program which runs under LabVIEW development environment is used for control of the measurement system and for data acquisition and its processing.

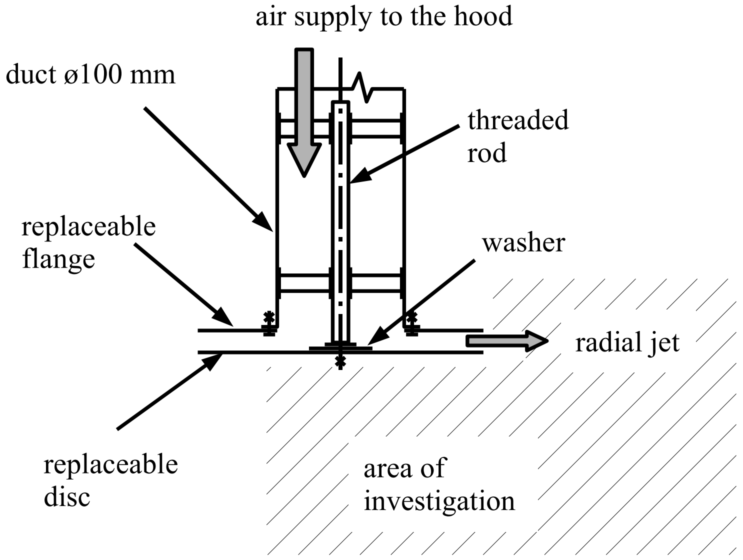

Figure 1 Scheme of the air terminal device for radial jet generation

For measurement of velocity profiles and turbulence intensity across the radial jet, thermal anemometry with hot element sensors is used. For accurate positioning of anemometry sensors over the area of interest, an automatic three axis traversing mechanism is employed. Visualisation system with smoke generator and digital video camera is also used.

Modelling

The radial jet was also simulated numerically by means of a commercial CFD code StarCD. The aim of CFD simulations is as using this tool for further development and optimisation of radial jet reinforced exhaust system.

A simplified sector like geometry was used (6 m in diameter, 6 m in length and 4° of central angle of the sector). A structured mesh was then employed in the way areas of expected high velocity gradients contained more computational cells than areas of small gradients. A second order MUSCL type spatial discretisation with TVD limiter was applied to the mesh [5]. As Reynolds number of the flow at the slot reached 2000, the flow was considered turbulent and a case study of turbulence models has carried out considering k-ε, RNG k-ε, k-ω turbulence models. The fluid (air) was treated as isothermal and incompressible.

Velocity profiles across the jet at various distances from the jet origin were also considered in the numerical study. The profiles computed with the use of different turbulence models were compared. As the jet induced axial flow within the domain, this phenomenon was also evaluated so to show effects of slot width and of three types of velocity profiles imposed at the slot (piston-like, parabolic and polynomial). Another parameter inspected within the study was that of the turbulence intensity at the supply slot. Four cases of turbulence intensity were considered, 5 %, 10 %, 20 % and 40 %, in particular.

Discussion of the Results

The basic set-up for both experiments and simulations was the following: initial velocity 10 m/s, slot width 4 mm and flange diameter 200 mm. For the purpose of validation, the set-up varied so the slot widths were 2, 4, 6, 8 mm. Velocity profiles across the jet were measured at distances from the air terminal device stepping from 0.1 m to 1 m (0.1 m step size). The crosswise distance of the probes was 1.5 cm which was found not sufficient to cover the velocity profiles close to the supply slot (0.1 m and 0.2 m). It was decided to relocate the probes in a staggered manner so 7.5 mm distance was achieved. Therefore the distance of the probes was 1.5 cm which was considered enough to prevent mutual influence of the 3 mm in diameter probes.

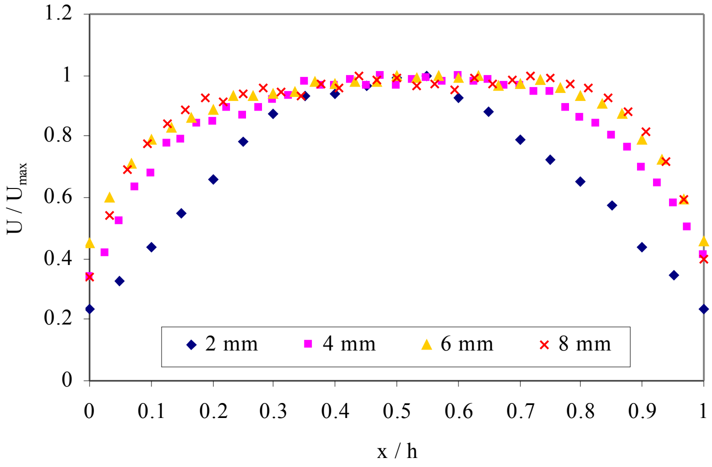

Figure 2 Velocity profiles for different supply slot widths at distance 2mm from the slot

The comparison part shall start with Figure 2 shows velocity profiles across the slot measured at a distance of 2 mm from the supply slot. The mean air speed at the slot had to be adapted not to exceed the maximum for the used anemometer so it was 5 m/s for this set of measurements. A hot-wire anemometer Schiltknecht ThermoAir3 was employed for this measurements. Due to the probe design, it was not possible to carry the measurements of velocity profiles at the very slot so 2 mm distance of the probe from the slot was used. It can be seen the distance was not suitable as the velocity profile was affected by the surroundings for the 2 mm slot. The 6 mm and 8 mm slot velocity profiles were almost not affected thus the 2 mm distance was well inside a core region of the jet.

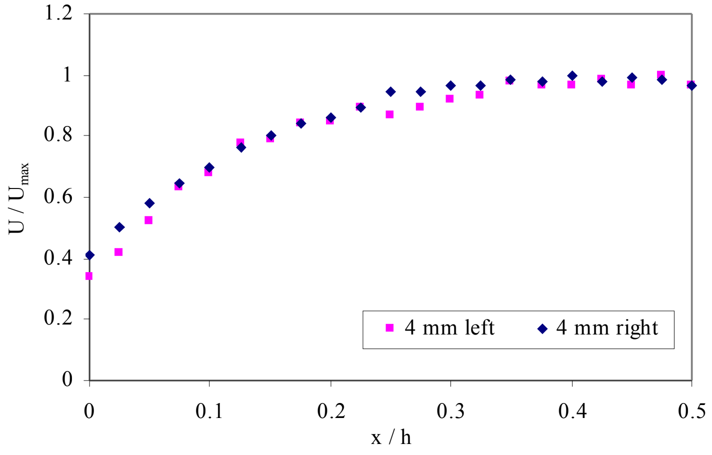

Figure 3 Symmetry of the velocity profile as generated by the terminal

Figure 3 is an extract of the data present in Figure 2; 4 mm slot width in particular. It shows the profile, generated by the terminal device, can be considered to be symmetrical. This is based on the fact that splitting the 4 mm slot profile in its centre and then flipping the right part of the profile to the left produced two sets of points with negligible variation; meaning 2.6 % for the best fit encountered with 6 mm slot, and 4.7 % for the worse and 8 mm slot.

Figure 4 illustrates dimensionless velocity profiles as they develop along with distance from the supply slot. The factor applied to the normalisation process was the maximum velocity of each investigated profile. It is clearly seen in the figure the axis of the jet measured departs from a geometrical axis of the slot (solid line intersecting zero *x* value), causing the jet to be not totally radial; the actual variation from the geometrical axis was about 2º. The measured profiles (a hot globe five probe anemometer TESTO 454) are compared with the data obtained by means of CFD modelling. The depart encountered with the measurements is not present with the modelling because of the inlet velocity at the supply slot was kept fixed across the slot and the velocity direction was set to be just radial.

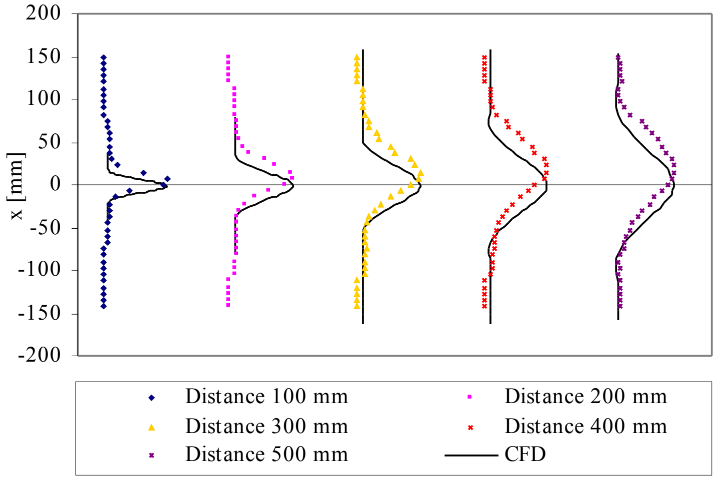

Figure 4 Dimensionless velocity profiles at different distances from the supply slot of the terminal device

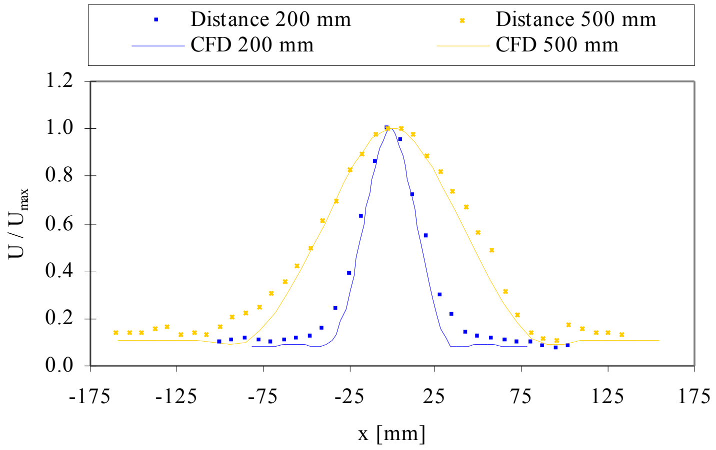

Figure 5 Velocity profiles at two distances from the supply slot (jet axes aligned)

As it has been indicated in Figure 4, the measured jet slightly diverted from the slot axis thus measured velocity profiles could not be compared with the results of CFD simulations if the profile shapes were to be assessed. In order to make profile comparison possible, two of the profiles were edited to fit in location. Results of the manipulation are depicted in Figure 5. One can conclude, there was a rather good agreement between the measurements and modelling achieved. Yet the accuracy of the simulation results is not convincing when looking at the velocity profile bottoms. It should be mentioned here that the turbulence model applied to the simulation which results are compared in the figure was standard *k*-ε turbulence model.

Figure 6 goes further in the comparison of the modelling with the measurements as it shows results of a three turbulence models against the measured data. In the figure the standard *k-ε* compares favourably with the other models despite deficiencies at the profile bottom.

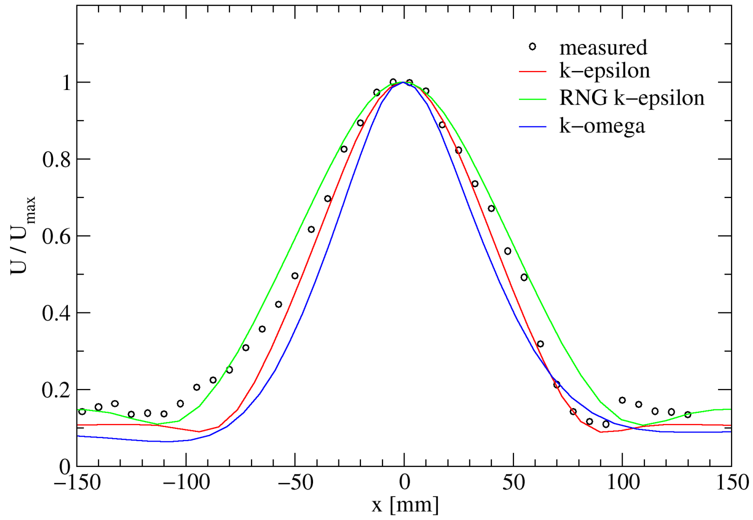

Figure 6 Radial jet cross-profiles at 50 cm distance from the supply slot

At this stage, we leave the velocity profiles across the jet and will proceed to the velocity distribution along longitudinal axis of the terminal device, i.e. axial velocity in the jet induced flow. The air speed at the slot was kept constant and at the value of 10 m/s in for this analysis. It is obvious the wider the slot, the greater flow rate and momentum flux thus the greater induced flow in axial direction as can be seen in Figure 7. Doubling the slot width from 2 mm to 4 mm resulted in 32 % increase in the maximum velocity in axial direction. Further doubling led to another 33 % increase but when the doubling was done for the third time the amplification effect lowered so only 28 % was achieved.

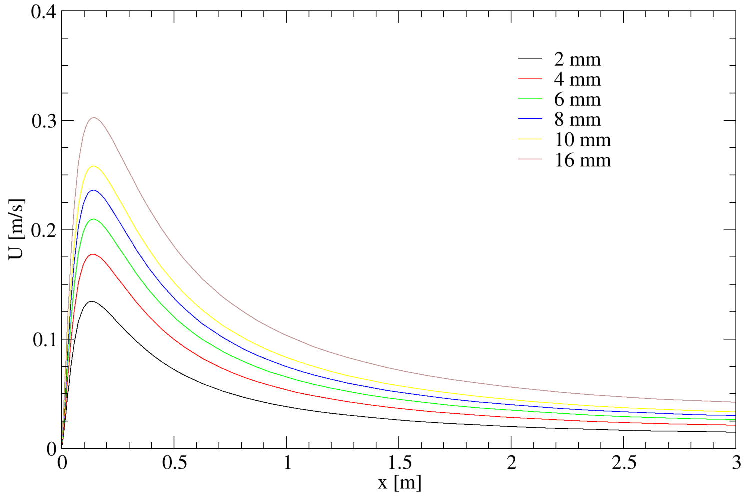

Figure 7 Induced axial velocity as a function of supply slot width

Figure 8 indicates effect of imposed turbulence intensity at the slot opening. As expected, increased turbulence level enhanced mixing of the jet with surrounding air, leading to amplified air entrainment by the jet. The effect of increased turbulence resulted in an extra 8 % of built-up air speed in front of the terminal device when comparing maxima of 5 % and 40 % turbulence intensity results. Although not shown here, imposing a velocity profile at the slot resulted in similar data. If this was the case, the cause of increased axial flow is different though and it can be explained by the jet momentum flux. The parabolic or polynomial profiles have greater momentum fluxes than the piston profile despite having the same average values.

Both jet spreading rate and spreading angle of the jet were assessed as well. These were evaluated based on two experimental methods. The first one was a smoke visualisation and one of it's results is shown in Figure 9. Although the method is quite simple, it proved to be very efficient in obtaining the spreading angle of the jet, and the direction the jet blown. Unfortunately, it is quite elaborate when trying to automatise the evaluation process. As the jet spreads in radial direction, the picture quality taken by a camera is deteriorated by the jet so the jet boundaries are difficult to recognise. The result of an averaging process carried out on five snapshots in a sequence is depicted in Figure 9.

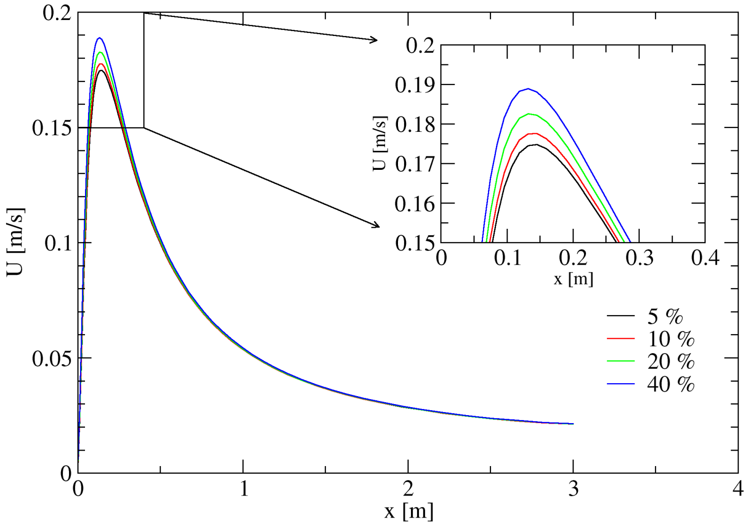

Figure 8 Induced axial velocity as a function of the turbulence intensity at the supply slot

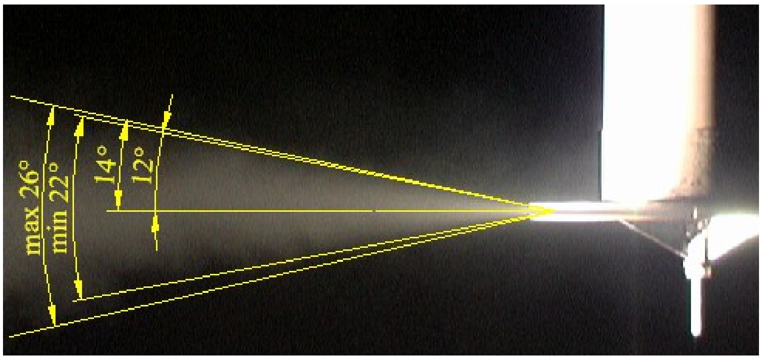

Figure 9 Smoke visualisation of the radial jet at 10 m/s of the air speed at the supply slot of the width 4 mm

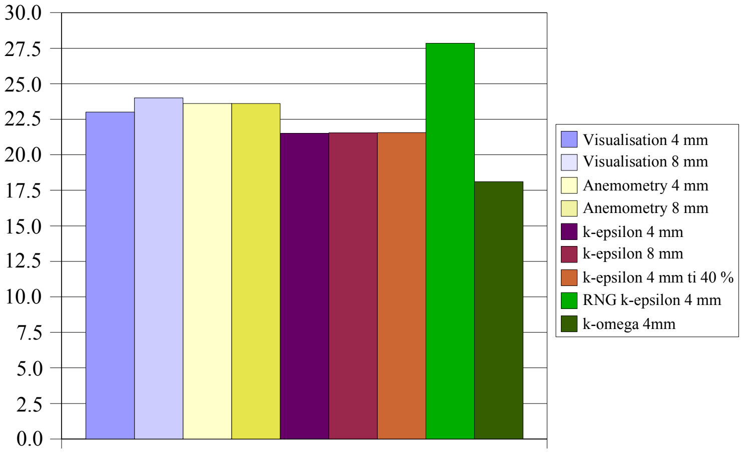

Figure 10 Spreading angle of the radial jet

The spreading angle was also evaluated based on velocity profiles measurement by hot globe anemometry at five locations with consecutively increasing distance from the slot. In this way, four values of spreading angle could be obtained and after taking the mean for the set it was included into the chart in Figure 10. It is clear the measured data agree well no matter which of the methods was applied. The standard *k-ε* turbulence model compares favourably to the other models as it reaches error of 10 %. Its accuracy has not changed with slot size or initial turbulence intensity of the jet; all simulations were performed with turbulence intensity of 10 % but the one labeled ‘k-epsilon 4 mm it 40 %’ where it was set to 40 %. Moreover, the standard *k-ε* turbulence model was off the range reported by Wilcox by 4 % only [6]. The least efficient turbulence model for radial jet modelling considered within the study was the RNG *k-ε* of which the error reached 30 %.

Conclusions

Radial jet characteristics have been evaluated by means of CFD modelling and measurements. The modelled velocity profiles across the radial jet showed a good agreement with the measured data. The measured spreading angle of the radial jet was 23.6° with standard deviation 1.5 %. When the modelled data were compared with the measured one, the standard *k-ε* turbulence model was the best among the chosen ones being just 10 % apart from the measured average. The smoke visualisation method proved to be very efficient in determining the spreading angle though having some drawbacks.

The study on supply slot width effect on the induced axial flow resulted in quite obvious statement: the broader the slot, the greater induction. Nevertheless, the gain was not proportional to the slot width thus the momentum flux as there was a maximum in the gain found to fall to the slot with of 8 mm. It was also shown the level of initial turbulence intensity at the supply slot influenced the induced flow as well. The higher the turbulence intensity, the stronger the flow. The maximum increase reached 8 % for turbulence intensity of 40 % when compared with results of the 5 % turbulence intensity simulation. Similarly to the increased turbulence intensity, the imposed velocity profiles either parabolic or polynomial increased the induction.

Acknowledgement

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