

Development of a free jet generated by an axial turbine in an open space Application to Ventilation in Fire Fighting (VFF)

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Abstract

In order to secure the operations in fighting enclosed fires, fans are used to create a positive pressure inside burning building to drive out smokes, heat and toxic species through every outflow opening existing. The pressure is created by the action of the jet generated by the fan turbine, usually a propeller. The fan is a portable device set down on the floor towards an opening so that the kinetic energy of the jet is transformed into potential pressure inside the first compartment. The efficiency of that kind of fan depends on the characteristics of the generated jet and also on the location of the fan in front of the inflow opening. This presentation proposes an experimental study of the development of annular jets at 100,000 Reynolds number which represents the jets generated by axial turbine. A second part reports a direct experimental study of the fan jet in conditions similar to real use conditions to show the influence of the floor, of the swirl effect due to the turbine rotation and of the inhomogeneities due to the obstructions of the engine driving the turbine. At last a definition of the efficiency of that kind of fan is proposed with the corresponding setup. This study deals to point out the two characteristic curves of that kind of fan, e.i. the flowrate as a function of the distance of the fan from the opening and the pressure/flowrate curve.

Introduction

One of the main difficulties in fighting fires in enclosed spaces are the smokes produced by the combustion because of their high temperature, their toxicity and because of their opacity which entails the loss of visibility. The main consequence is the increasing of the fire fighters difficulties in their action, especially to find fire and to rescue peoples held up inside the compartments where the smoke spreads. Another consequence of the smoke spreading is the combustion propagation because of the heat. A solution to overcome the barriers and the difficulties so created by the smokes lays in forcing them to get out by the shorter way. This method consists in creating a positive pressure inside the enclosed spaces. This pressure is produced by the action of a free jet on an opening which is generally the door by which the firefighters come in and out. Another opening is used as smoke exhaust. This last one may be a window or another door or it may be created by opening a hole in a wall or in the roof. The jet is produced by a portable fan brought on fire fighting place by fire fighters. This method is called positive pressure ventilation (PPV). In spite of its real effectiveness in specific cases this method presents two kinds of problems. The first one concerns the possible consequences on the fire. One of them is called backdraught, this is an explosion due to the oxygen directly injected by the air jet inside the spaces in which smokes at high temperature spread. The study of this first problem deals with researches on ventilation in fire fighting (VFF). The second problem is the efficiency of the devices used to create the air jet which must produce the positive pressure inside the enclosed spaces in which the smokes spread. This efficiency depends on several parameters the two main are i) the nature of the air jet created and ii) the location of the fan towards the opening on which the jet must create the positive pressure. The subject of this paper is to present the results of the study which we carried on the air jet nature and its action on the opening. The problem of the consequences on backdraught and on fire spreading concerns others research areas not presented here.

To create the positive pressure inside a building in which there is a burning compartment, the fan is located outside towards an opening, a door for instance, blowing into the first compartment in which kinetic energy is transformed into pressure inside all others compartments of the building. Such a pressure induces an outflow through every opening or hole it would exist in these building. So that the smoke is driven outside bringing out heat and toxic species. If there is no opening or hole to drive out the smoke, a hole may be made by the firemen in a wall or in the roof. The Fig 1 represents the principal of this method. On the left side there is a portable fan located in front of the door at a distance we are discussing in this paper. On the right side there is a compartment which represents all the compartments of the building in which the fire spreads and in which the positive pressure is created by the air jet produced by the fan.

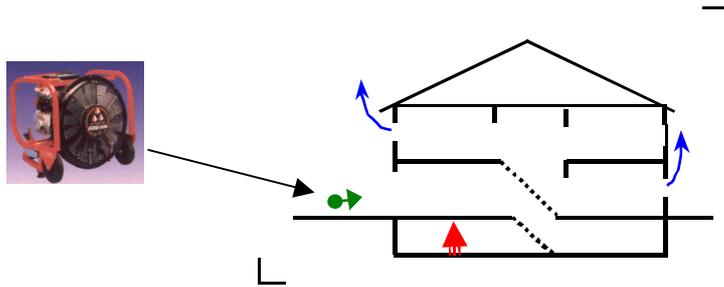


Fig. 1 : The principal of the positive pressure ventilation in fire fighting. On the left side there is a portable fan located in front of the door at a distance D . On the right side there is the building in which the fire spreads and in which the positive pressure is created by the air jet produced by the fan. Pieces that make up a fan used for the positive pressure ventilation in fire fighting are an engine, an axial turbine (usually a propeller) and a protection grid.

The higher the pressure created inside the building is, the higher the outflow of the smokes is and the more efficient this method will be. Creating a high pressure inside the building needs an efficient action of the air jet on the section of the door to transform the kinetic energy into pressure. It is important to notice that the fan must be located at a distance higher than one meter and a half from the door to keep free the way in and out for the firemen operations. Furthermore the action of the air jet on the door section prevents the smoke outflow which makes easier the firemen operations. The main questions induced by this method are what is its efficiency, what must be the structure of the air jet, where the fans must be set down? To bring out answers to these questions a study of the air jets produced by the fans had to be carried on.

Many researches were carried on to study jets. Most of them dealt with jets Reynolds number under 10,000, while the Reynolds number of the usual fans is about 100,000. Nevertheless the results of these studies give us many informations to get a better understanding of the fan jet. The first reference work on the subject is the Abramovitch analysis carried on the turbulent round jet. One of the main results was to show the autosimilarity of the velocity field inside the jet along its axis. A free jet becomes an annular jet when a disk is located in the centre. This case was studied by Durao and Whitelaw who showed that a velocity recirculation zone is created in the near wake of the disk. The far velocity field is modified by the disk, nevertheless the flow develops in a manner similar to a turbulent round jet flow. A free jet may be modified by a swirl as it was shown by Billant & al. in their experimental study of vortex breakdown in swirling jets. The modification of the jet by the swirling effect depends on the swirl parameter S and its critical value $S_c=1.3-1.4$. At S_c a stagnation point appears in the weakly turbulent region of the swirling jet independently of the Reynolds number value, this can give birth to several distinct configurations depending on the Reynolds number value. Steenberg and Voskamp have shown that the swirl decay in the streamwise direction of a flow in a duct mainly depends on the Reynolds number. The inhomogeneity of jets were partly studied by Liepmann and Gharib. in a study of the role of streamwise vorticity in the near-field entrainment of round jets. They pointet that inhomogeneities lergely develop for high swirl number while they vanished for law swirl number. In a study of the effect of the initial velocity profilee in round jet, Ferdman and al. shown that the inhomogenities may vanish in the streamwise far velocity fied with a decreasing of the velocity.

All of these studies led us to point out the different aspects of the jets which had to be studied in order to increase the efficiency of the fans used in this ventilating method used in fire fighting. These different aspects are the consequences of the fan design. These aspects are mainly the annular jet, the effect of inhomogeneity of the initial velocity field of a jet, the swirl effect of a jet and the effect of a wall on a jet. These portable fans are formed of three main parts : an engine on which an axial turbine, a propeller, is directly connected and a protection grid just after the turbine. Moreover, the construction sizes must be as short as possible because of the necessity to be able to put the fan inside the fire vehicles.

The characteristic of the jet directly depends on this specific construction characteristics. The jet is widened more rapidly because of the swirl created by the turbine. The jet does not remain axisymmetric because of the non regularity of the obstructions created by the engine located just before the turbine. The initial velocity field is not of a top hat shape because there is a central obstruction due to the turbine hub. And furthermore, the floor on which the fan must be put down during the operations induce modifications in the jet velocity field.

All of these aspects lead us to study the fan jet through three ways.

- 1) the analysis of annular jet for a Reynolds number corresponding to the real situation, in order to take the turbine hub effect into account, and to define the optimal internal and external diameters of the turbine,
- 2) the effect of the swirl, the turbulence and the floor on the development of the jet between the fan and the opening,
- 3) a comparison analysis of the fan efficiency in real conditions to a qualification test.

Velocity field in annular free jet at high Reynolds number

Due to the effect of the turbine design, the produced jet is an annular shape. There is a central part of the jet in which the initial velocity is zero because of the turbine hub. The study consists in analysing the effect of the hub wake in the development of the streamwise velocity field in order to define the optimal internal and external diameters to be used in that kind of fan. In this section, the first step in all the tests was to verify the selfsimilarity of the velocity profile in the streamwise direction. In the case of the annular jets a recirculation zone is created just near the central obstruction, the velocity profile is nevertheless selfsimilar but only after this recirculation zone. The self similarity allowed to study the velocity field of the jet along a radius only in one crosswise plane. Because of the usual use conditions this distance was chosen to be equal to 3m from the opening. All the results of the section were compared in these specific test conditions. The study was carried on through two series of tests : one with the same initial flow rate and the second with the same initial power of the jet.

The first one consisted in three types of tests in which the initial flow rate remains the same, its value was of $10,000\text{m}^3/\text{h}$. These three types of tests and their results are :

- 1) for a free jet in which only the initial diameter was varying, the most powerful jet at 3m is obtained with the lowest initial diameter,
- 2) for an annular with a constant external diameter of 0.55m while varying the internal diameter, the most powerful jet is obtained with the greatest internal diameter,
- 3) for an annular jet with a constant initial section while varying the middle diameter, the greater the middle diameter is the lower powerful the jet is.

The second way consists in three types series in which the initial power of the jet remains the same. The results are as followed :

- 1) for a free jet, whatever is the initial diameter in the range from 0.35 to 0.65m there is no significant change in the velocity profile at 3m from the initial section,
- 2) for an annular jet with an initial diameter of 0.55 or with a constant initial section of 0.1m^2 , the internal diameter must be as lower as possible to have the most powerful jet at 3m from the initial section.

The whole series of these tests have shown that to have a powerful jet the external mixing surface must be as small as possible. The Fig. 2 shows the results for the annular jets at same initial power with first the same initial diameter of 0.55m and second the same section of 0.1m^2 . Others tests were carried on with the same grid that the protection grid used in real conditions, these tests have shown that the turbulence is weakly modified beyond the central recirculation zone.

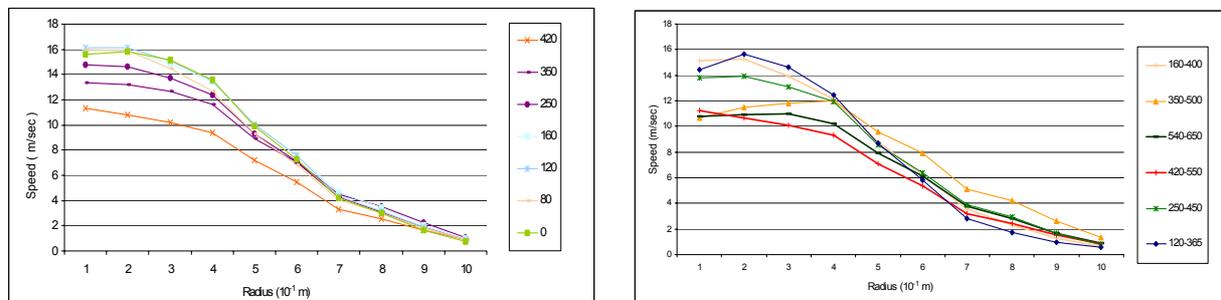


Fig. 2 : the velocity profile at a distance of 3m from the initial section with the same initial power, on the left with the same initial diameter of 0.55m and on the right with the same initial section of 0.1m^2 .

Effects of the swirl, the initial non-homogeneity and of a wall on the development of the jet generated by a fan turbine

In the previous section, considering a jet from a turbine as an annular jet with a swirl and inhomogeneities we have analysed annular jet alone to define the necessary condition to remain a powerful jet at a distance of 3m from the initial section. In this section we present the results of the study of the jet generated by fans in real conditions.

The first concerns the effect of a wall on the jet. Because of the specific use conditions, the fan set down on the floor so that modifications are induced in the development of the jet. In a first step a numerical test was carried on with a NSPP code with initial velocities given by measurements on a fan setting down on the floor. The Fig 4 shows two results computed with two angles between the turbine axis and the floor (e.i. the wall) 0° and 5° , respectively. The results are shown in a vertical plan so we can clearly see the effect of the wall which induces a dissymmetrical velocity field in the streamwise direction. The velocities remain important near the floor while they are decreasing in the upper zone because of the mixing effect with the external zone. As shown on the Fig. 3, the floor effect appears to be less important when the slant angle of the turbine axis increases.

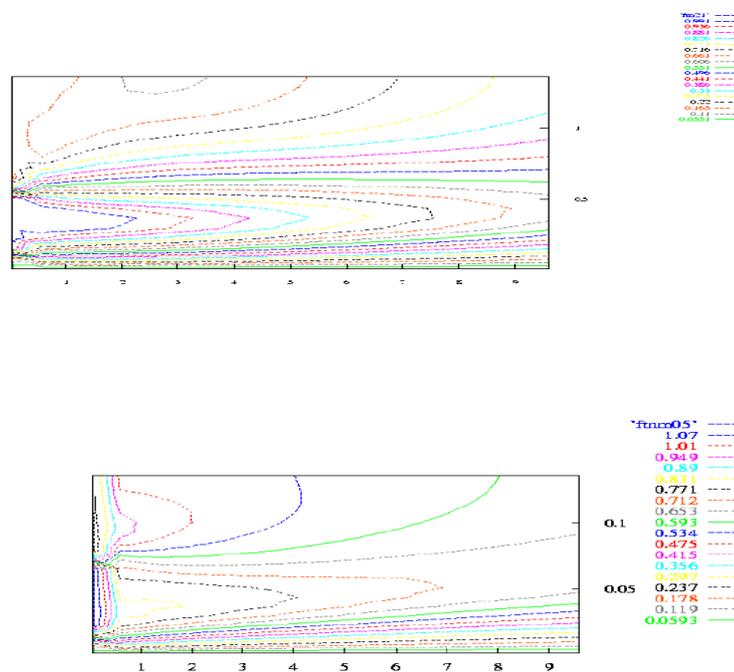


Fig. 3 : Computing results of the floor effect on a jet generated by fan turbine setting down on the floor. The result shows that the decrease of the velocities is less important near the floor while it is more important in the upper zone because of the air entrainment effect. The angle between the turbine axis and the floor is 0° on the right side and $+5^\circ$ on the left side. In both cases the initial velocity has a top hat profile with a magnitude of 25m/s.

Now we present the comparison between the velocity fields produced by two kinds of fans in order to show simultaneously the effect of the wall and of the inhomogeneities. The inhomogeneities are due to the location of the engine just before the turbine. The initial power is the same for every fan :

- A is a compact fan, the turbine is a fourteen blades propeller with an external diameter of 0.45m and an internal diameter of .2m,
- B is a fan which turbine is an eight blades propeller with an external diameter of 0.65m and an internal diameter of 0.1m,

The Fig. 4 shows the velocity fields in five crosswise plans, the first one is the initial section and the others are located at distances of 0.5, 1, 1.5 and 2m from the initial section respectively. The fan A velocities fields are shown for three values of the angle between the turbine axis and the floor, 0° , 10° and 20° , respectively in order to detail the spreading effect on the floor as a function of the slant angle. The fan B velocities fields are shown only for one value of the angle between the turbine axis and the floor in order to be compared with the fan A velocities fields. As it will be pointed out the angle 20° is the slant angle usually used in real conditions.

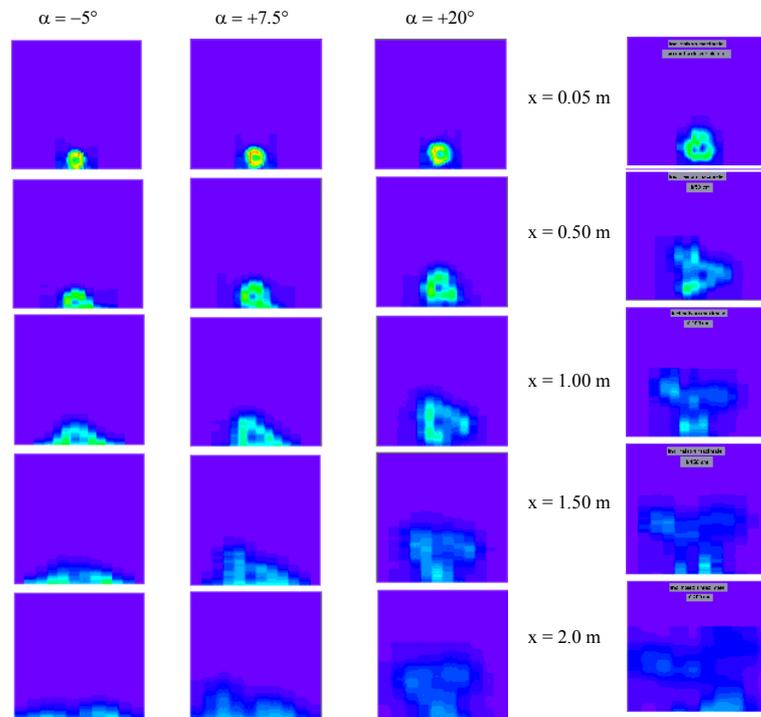


Fig. 4 : the velocity fields in five crosswise plans for two fans A and B set down on the floor. The space between two plans is 0.5m, the first one is in the initial section of each jet. A is a compact fan which turbine is a fourteen blades propeller with an external diameter of 0.45m and an internal diameter of .2m, and B is a fan which turbine is an eight blades propeller with an external diameter of 0.65m and an internal diameter of 0.1m,

The three columns on the left side on the 4 shows the spreading effect due to the floor analysed for the A fan. For a zero slant angle the jet becomes largely flat at a distance of only 2m, e.i. about 4 diameters from the initial section. Its thickness is about one diameter while its wideness is upper than 5 diameters, e.i. a thickness of about 0.45m and a wideness of about 2;5m. For the slant angle value of 10° the same phenomenon appears but with a less effect, the thickness is greater and the wideness smaller. On the other end when the slant angle of the turbine axis is 20° the effect of the floor is largely reduced, so that the jet remains compact and quasi-axisymmetric and its characteristic diameter is about 2 initial diameter, e.i. about one meter.

The right side column shows the development of the velocity field for the B fan with a slant angle of 20° , e.i. an angle for which the spreading effect due the floor is minimum. In this case the spreading effect due to the floor is once again reduced but with a less magnitude.

Furthermore it is to be noticed that for the B fan the jet appears to be splitted into several parts with lower velocities than in the case of the A fan in the same conditions shown in the column just on left side. The splitting effect is due to the inhomogeneities in the initial velocity field. These inhomogeneities are due to of the partial obstruction of the engine located just before the propeller. There is a same phenomenon with the A fan, but its initial mean velocity is higher and its initial diameter is smaller so that the inhomogeneities partly disappear in the streamwise direction, this is not the case for the B fan which initial velocity is lower and its initial diameter higher. It is also to be notice that for the A fan the velocity at 2m from the initial section is about 20% higher than for the B fan, this will have consequences on the efficiency of the two fans which is to create a positive pressure in the compartment.

The jet sizes at 2m from the opening, wideness and thickness, must be compared to the sizes of the door, 1m wide and 2m high, in the section of which the jet must be directed to create a positive pressure in the compartment. This shows the importance of the negative effect of the floor when the jet slant angle is too small, 0° or 5° for instance.

The comparison between the two fans A and B leads to the same conclusion which was defined in the previous section, e.i. for the same initial power of the jet the more powerful jet at a distance of two meters from the opening is obtained with the fan turbine which diameter is the smallest.

In others respects, we have noticed in these tests a weak decrease of the swirl effect due to the floor

Comparison analysis of the fan efficiency in real conditions and definition of a qualification test

Because of the effects of the swirl, of the floor and of the inhomogeneities, the whole previous results show that it is impossible to establish the efficiency of a fan only by the measure of the initial velocity field. So that the efficiency must be established through a method giving directly the pressure created inside the compartment as a function of the fan location in front of the opening. As shown on Fig. 5, this method consists to set down the fan on the floor towards an opening of a compartment in which there is another opening on the other side for the outflow. Inside this compartment the jet is broken down with a grid and the homogeneity of the velocity field is controlled with a honeycomb. The cross-section of the compartment is equal to ten times the outflow section. In this test the opening section and the outflow section have the same surface. The inflow opening represents a door towards which the fan may be set down in real operating conditions.

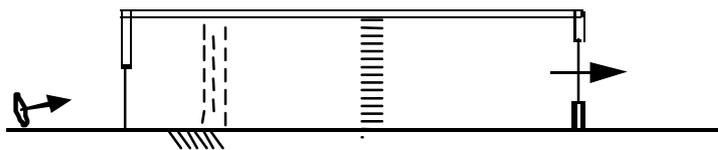


Fig. 5 : The principal of the test setup with the opening towards which the fan is set down on the floor, inside the compartment the grid to breakdown the jet and the honeycomb to control the homogeneity of the flow field, on the other side the outflow opening.

This setup allows to get two kinds of characteristics of a fan. The first one is the flow rate created by the fan as a function of the distance D from the door and as a function of the slant the turbine axis. An exemple of this test is given on the Fig. 6 for three fans, the fans A and B and another one. The A fan cracteristic appears to be flatter with higher values than the B fan characteristic, this result confirm the conclusion of the analysis carried on in the two previous sections. This test directly shows that the distance D range for the A fan to be used with the highest flowrate is 1.5m to 3m while the one for the B fan is only 1m to 2m.

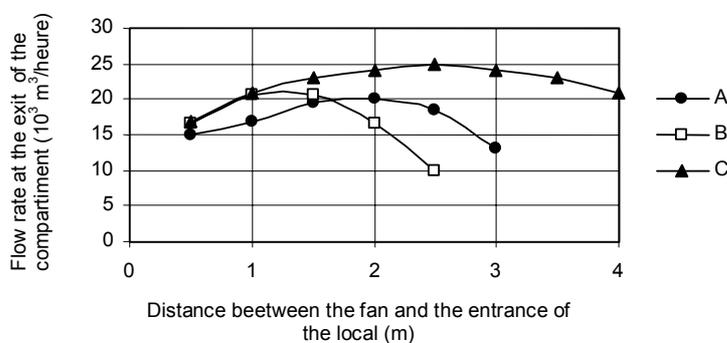


Fig. 6 : The direct flowrate test for the A and B fans as a function of the distance D from the opening. C is an other of the same initial power with lower obstructions.

The second characteristic is the pressure created inside the compartment as a function of the outflow opening size for each distance D and for each slant angle. As an example of this test is given on the Fig. 7 which shows the comparison between the A fan and the B fan. The B fan curve slope is lower than the A fan curve so there is a cross point at about a pressure of 5Pa under which the B fan gives the greatest flowrate while above this point it is the A fan which gives the greatest flowrate. We have to notice that in most fires the pressure created is higher than 10Pa so that the A fan gives the best efficiency in most cases.

The efficiency of a fan is directly given by both curves, the flowrate as a function of the distance D and the pressure / flowrate characteristic.

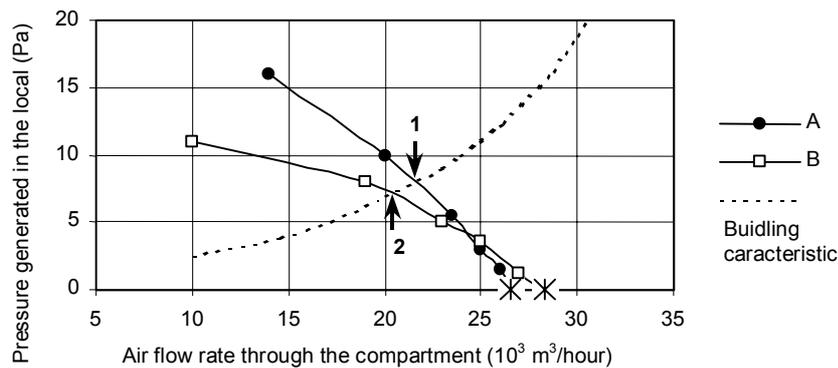


Fig. 7 : Comparison of the pressure / flowrate characteristics of two fans, 1 is the A fan and 2 is the B fan.

Concluding remarks

Because of the simultaneous effect of the swirl, of the inhomogeneity and of the floor, this study has shown that the analysis of the jet generated by the turbine of the fan used in real fire fighting condition must be analysed through tests reproducing the real use condition. Nevertheless it is clear that the results pointed out through experiments on annular jets may be partly applied for the real jet generated by fans under the condition of reducing the characteristic length which is about 10 diameters in annular jet while it is only 4 diameters in the real turbine jet. The swirl effect of a turbine jet decreases because of the floor effect. This floor effect which induced a spreading of the jet involves to use the fan with a minimum slant angle of 20° in real condition.

These experiments have clearly shown that the efficiency of fans specially designed for fire fighting use must be defined with two characteristic curves, one is the flowrate as a function of the distance from the opening and the second one is the pressure versus flowrate curve as a function of each position.

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Keywords

Jet, fan, turbulence, swirl, annular jet, efficiency, ventilation in fire fighting;

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