HAIFU WANG, Ph.D.
E-mail: haige2013@yeah.net
LIANGCAI CAI, Ph.D.
E-mail: liangcai07@126.com
XIAOLEI CHONG, Ph.D.
E-mail: 546975300@qq.com
HAO GENG
E-mail: genghao8807@163.com
Air Force Engineering University
No.1, Baling Road, Baqiao District,
Xi'an city of Shaanxi province, PR China

Safety and Security in Traffic
Review
Submitted: May 10, 2014
Approved: Mar. 24, 2015

EXPERIMENTAL STUDY OF THE JET ENGINE EXHAUST FLOW FIELD OF AIRCRAFT AND BLAST FENCES

ABSTRACT

A combined blast fence is introduced in this paper to improve the solid blast fences and louvered ones. Experiments of the jet engine exhaust flow (hereinafter jet flow for short) field and tests of three kinds of blast fences in two positions were carried out. The results show that the pressure and temperature at the centre of the jet flow decrease gradually as the flow moves farther away from the nozzle. The pressure falls fast with the maximum rate of 41.7%. The dynamic pressure 150 m away from the nozzle could reach 58.8 Pa, with a corresponding wind velocity of 10 m/s. The temperature affected range of 40°C is 113.5×20 m. The combined blast fence not only reduces the pressure of the flow in front of it but also solves the problems that the turbulence is too strong behind the solid blast fences and the pressure is too high behind the louvered blast fences. And the pressure behind combined blast fence is less than 10 Pa. The height of the fence is related to the distance from the jet nozzle. The nearer the fence is to the nozzle, the higher it is. When it is farther from the nozzle, its height can be lowered.

KEY WORDS

jet flow; blast fence; experimental research; dynamic pressure; temperature;

1. INTRODUCTION

With the rapid development of the world aviation industry, especially with the advent of large and heavy jet aircraft, the velocity of the tail flow that an aero-engine ejects has increased. It could reach 200 m/s when the flow is 15 metres away from the nozzle, which seriously affects the normal use of an airport. Therefore, the prevention and control of the jet flow have caught the attention of relevant departments of airports.

The jet flow is always at high velocity and temperature, affecting the safety of vehicles, reducing working efficiency, causing pedestrians and those who work near the aircraft maintenance apron or hangar access apron to produce unwelcome reactions, and even endanger their life safety. The discomfort that people suffer varies from person to person. A large number of statistical data indicates that the adults who are walking feel uncomfortable when the wind speed is at its upper limit of 15 m/s [1-5], which, however, is just utilized as an empirical value. The International Civil Aviation Organization (ICAO) stipulates that pedestrians and vehicles should not pass by when the flow velocity exceeds 15 m/s [6].

Due to the effects of external factors, the temperature and velocity of the jet flow decrease when the flow is away from the nozzle. If no measures are taken and the velocity drops to 15 m/s, then no people and vehicles are allowed to pass through the area of 200×100 m within an airport (that is to say, the area around 200 m along the axis of the aircraft, and 50 m are allowed to each side of its vertical axis) and this area cannot be effectively used. The range of the area differs from aircraft to aircraft. As people have gained an in-depth understanding of the harm of the jet flow, civil aviation organizations in all countries have installed in their airports anti-blowing facilities of different models, which can weaken the effects of the jet flow and improve the utilization rate of the apron.

The design and the study of blast fence and the effects of jet blast on people have been widely studied for last several decades. Early in the 1950s, W. J. Turnbull et al. studied the effects of jet blast on bituminous pavement [7]; Temple A. Tucker studied the blast fences for the requirements of USAF, and several kinds of blast fences for B-52 Bomber were discussed in [8]; the airport design advisory circular of FAA proposed principles for construction of blast fences based on the effects on jet blast, and several types of this facilities are suggested [9]. Hiroshi Kobayashi et al. studied about the wind shielding capabilities of blast fences by model experiment [10]. However, the applicability of each kind of blast fence is different for different types of aircraft; it is necessary to study the blast fence according to the aircraft for design parameters.

The jet flow field is tested in this paper to provide the parameters for designing the blast fence. A combined blast fence is introduced based on the characteristics of two types of typical blast fences. Experiments and research are carried out on the effects of 3 types of blast deflector fences, which will provide important reference value for the follow-up study.

2. THE DESIGN OF BLAST DEFLECTOR FENCE

At present, whatever materials are selected, the commonly used blast deflector fences can generally be divided into two types: the solid blast deflector fence and the louvered one.

The structure of the solid blast fence is similar to the retaining structure of a retaining wall, and whether or not it can play the key role mainly depends on the height and angle of the arc structure of this fence. If the fence is too high or steep, a strong echo and air flow resistance will then follow and adverse effects such as horizontal overflowing air current will be easily produced.

The louvered blast fence is composed of vanes and brackets. The vane has a specific angle to guide the flow, and the function of the bracket is to fix and support the vanes. The basic principle of the louvered blast fence is to use the vanes to make the jet flow diffuse up backwards along the vanes, which creates the weaker air resistance and exerts little impact on the aircraft. Nevertheless, as to its structure, there must be vanes, brackets and deep foundation, which is not only complex and costly, but also causes considerable difficulty in construction. What is more, there are problems with its durability.

Although the solid blast fences have better durability than the louvered ones, they will produce turbulence behind it. In order to avoid the harm caused by the turbulence, part of the fence can be made open to let the air flow pass through so as to abate the turbulence. With the combination of the advantages of both solid blast deflector fences and the louvered ones, a new type of blast fence, a combined blast fence, is proposed in this paper. Thus, not only can the cost and the difficulty in the construction of louvered fences be greatly reduced, but also the retraced turbulence that the solid blast fences may produce can be avoided.

The combined blast fence is displayed in the form that the solid blast fences and louvered fences are arranged alternatively according to a certain ratio. This ratio can be defined as solid-louvered ratio (S/L for short). The arc of the solid part is taken as 75° while the angle of vanes of the louvered part is taken as 40°. The distance between two vanes is 1/3 of the height of the vertical projection of the vane [11], as shown in *Figure 1*.

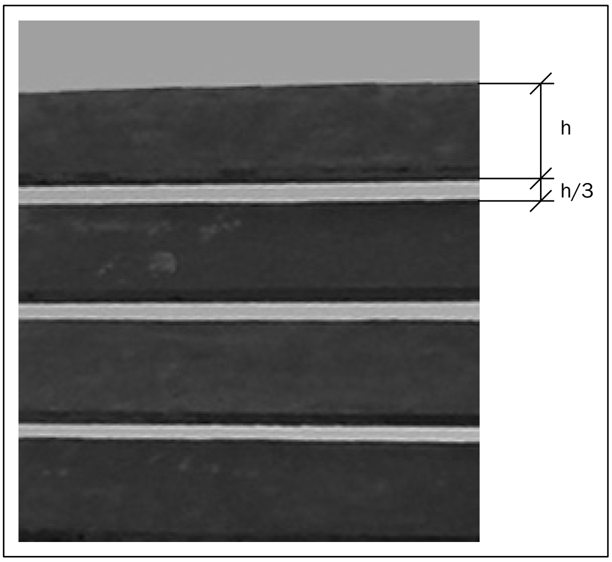

Figure 1 - Distance between vanes

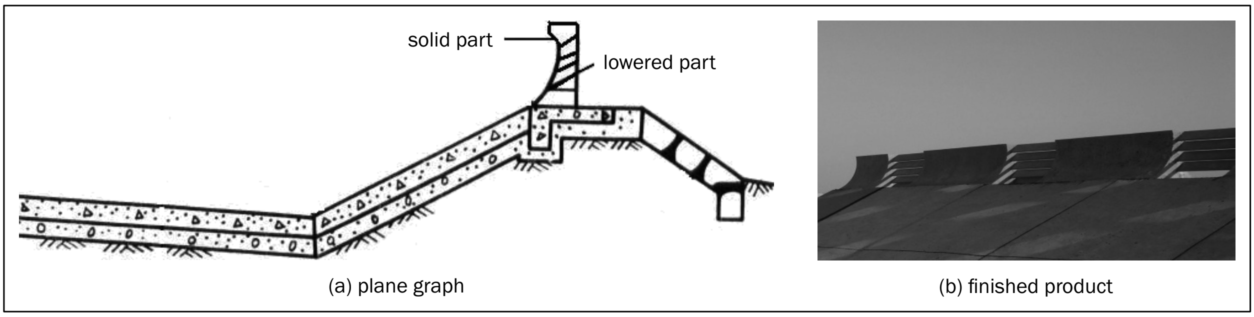

Figure 2 - Combined blast fence

The height of the fence and the *S/L* are determined based on the specific aircraft [12].The plane graph of a combined blast fence is shown in *Figure 2*(a), and *Figure 2*(b) shows the finished product.

3. EXPERIMENT DESIGN

3.1 Plans of experiment

The jet flow field of a certain aircraft is tested for the design of a blast fence. To study the effect, the test on three types of blast deflector fences is conducted for the comparative analysis. The temperature and pressure within the field are measured. As the velocity of flow can be calculated through its dynamic pressure and temperature, this paper mainly analyses the dynamic pressure distribution of the jet flow. The tests are made up of jet flow field (JFF) tests and jet blast deflector fence (JBD) tests.

The test on the jet flow field is carried out when the aircraft is in each of the four states: in idle thrust (2,500 r/min), in full load take-off thrust (4,000 r/min), in normal training thrust (3,500 r/min) and in maintenance thrust (4,700 r/min). As the blast fence is mainly used for aircraft maintenance, 4,700 r/min (revolutions per minute) of the engine in the fourth state is taken in the JBD tests.

Four types of experiments are conducted: the test of the jet flow field (A), the test of the solid blast fence (B), the test of the louvered blast fence (C) and the test of the combined blast fence (D). The height of the fences in tests B and C is 2 metres. In test D, two different kinds of heights are designed, namely, 2 m (D_1) and 2.5 m (D_2). The distances between these three types of blast deflector fences and the nozzle are shown in *Table 1*.

Table 1 - Position of tested blast fence in JBD tests

Distances from tail of nozzle (m)	25	35
Plan B	√	
Plan C	√	
Plan D1	√	√
Plan D2	√	√

3.2 Arrangement of test sections and measuring points

When the flow field is tested, 11 lateral sections are arranged at the distance of 15-150 m apart from the nozzle. On each section there are 11 measuring points. As the tested aircraft is twin engine aircraft and the distance between the two engines is 6 m, and the

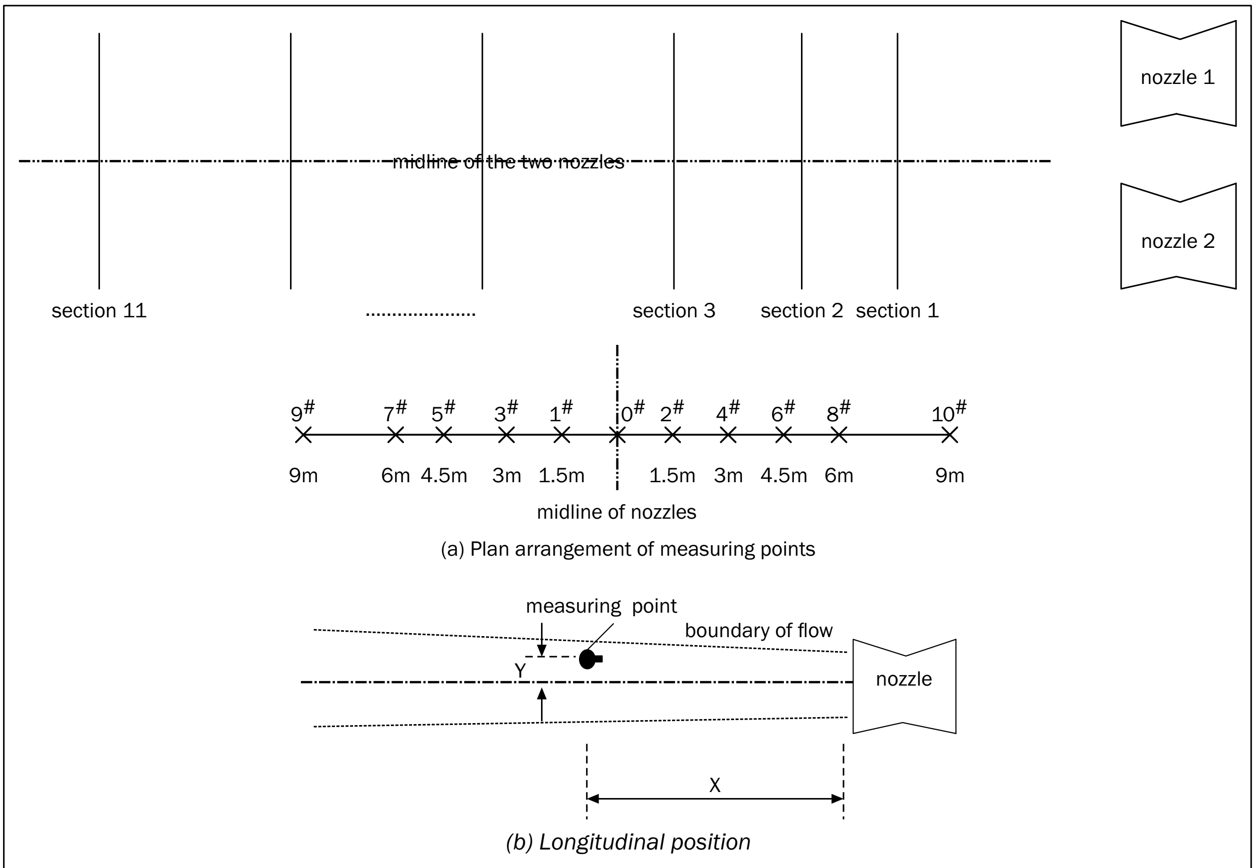

Figure 3 - Arrangement of measuring points

Table 2 - Position of test sections

Number of test sections	1	2	3	4	5	6	7	8	9	10	11
Distances from tail of nozzle (m)	15	20	25	35	45	55	70	90	110	130	150

tests mainly concern the centre pressure of each jet flow produced by the engine, with each side of the test section being 9 m, which is enough for the required centre pressure analysis. Since the safe velocity of jet flow is 15 m/s, if the dynamic pressure tested around a section is lower than 150 Pa (roughly equivalent to 15 m/s), then there will be no test on the next section. In the JBD tests, five sections are selected for a comparative study. They are 20 m, 35 m, 45 m, 55 m and 70 m away from the nozzle, respectively. The transverse measuring points of each section are the same as those in JFF tests. As the height of the nozzle centre is 2.5 m, then the measuring point should also be 2.5 m away from the ground behind the fence. Owing to the influence of air gravity and environment, additional measuring points can be added through the test equipment around the points along the centreline of the nozzle to catch the centre of flow. The distance between the sections tested and the nozzle is shown in *Table 2*. The arrangement of measuring points on each section is shown in *Figure 3*.

3.3 Experimental equipment

Armoured thermocouple and contact measurement method are adopted for measuring the temperature of the flow and the pitot tube is used for measuring the dynamic pressure. The pitot tube can measure the static pressure and the total pressure of the jet flow, and the dynamic pressure is calculated by the two pressures following the formula below:

$$P_D = P_t - P_s \tag{1}$$

where P_D is dynamic pressure of the jet flow, P_t is total pressure of the jet flow, P_s is static pressure of the jet flow. When analyzing the jet flow field, only dynamic pressure is used. Thus, the pressure refers to dynamic pressure further in the text.

A measurement rake is designed to facilitate the measurement. For the sake of accuracy, the sensing parts of pressure and temperature cannot be designed to be placed together. The measuring points of the temperature should be put above those of the pressure and be as close to the measuring points of the pressure as possible. The distance between the measuring points of the pressure and that of tempera-

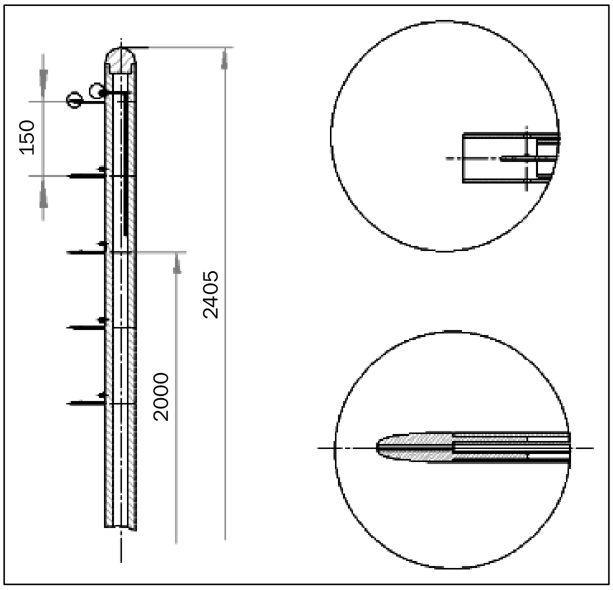

Figure 4 - Measuring point in measurement rake

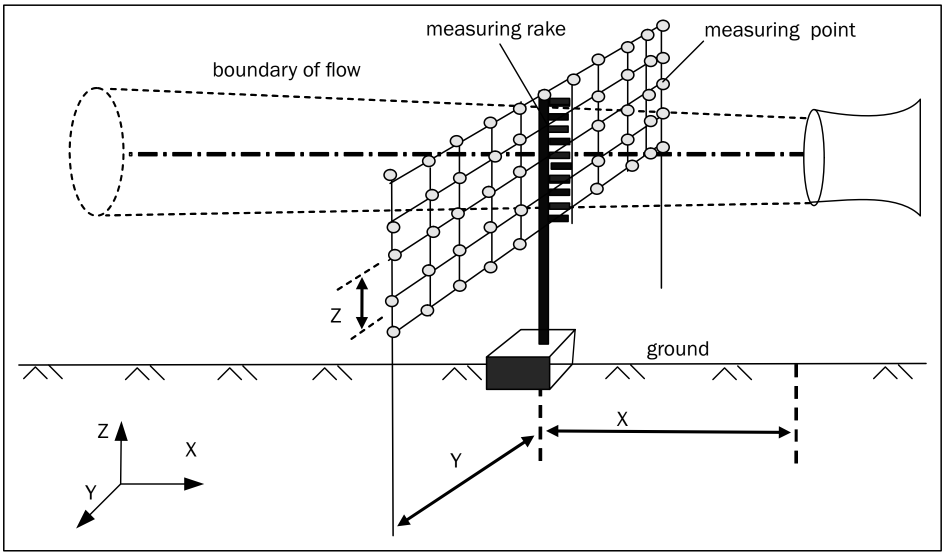

Figure 5 - Sketch map of the measuring rake

ture points tested is 10 mm [13] due to the technological problems, as shown in *Figure 4*.

The direction of axis Z in the measurement rake is already fixed by the measuring points of temperature and pressure (speed) in the measurement rake. According to the arrangement of measuring points, the direction of axis Y is unrestrictedly adjustable within the range of -9.0 - 9.0 metres, and the direction of axis X changes according to the measured sections, as shown in *Figure 5*. The measurement rake is composed of underpan, guide rail, pulley, chain, turbine, underpinning and other parts. Driven by a 0.75 kW motor, the pulley moves on the chain at a velocity of 4 m/min and can be controlled to stop at any position. The combined measuring rake is fixed by three points on the pulley and can move within a distance of 18 metres along the underpinning. The assembled measuring rake is shown in *Figure 6*.

In consideration for the particularity of the experiment and the large measuring area of flow parameters, the data are transmitted by the wireless, that is, all sensors are put on the pulley to send signals through a wireless transmitter (the distance of transmission is from 0 to 1,000 metres). These signals are then collected and stored by a wireless receiver of the data acquisition system. The sensor signal procedure and the receiving device are shown in *Figure 7*.

Figure 6 - Assembled measuring rake

4. Analysis of the results

The environmental factors exert great impact on the test. The natural wind produces a great effect on the jet flow. Natural wind acts as a positive force on the pressure or temperature while the headwind yields a blocking effect and even the crosswind deflects the jet flow. In the experiment, for example, when the crosswind is at 3 m/s, the flow of 4,700 r/min is blown to deviate 1.0 m from the centre-line after it is 70 m away from the nozzle.

Therefore, the tests must be carried out in clear and windless weather. If the weather is not perfect, the pressure, temperature and the wind speed of the environment should be recorded. In order to ensure the comparability of the results, the data tested should be pre-treated according to the pressure and temperature and be analyzed when they are converted into those in standard conditions (the standard air pressure, 15°C and no wind).

4.1 Aircraft jet flow field

It is found that the pressure could reach 58.8 Pa and the corresponding velocity of the wind is 10 m/s when the jet flow is 150 m away from the nozzle. The effect on one side could reach a maximum of 22 m. And the temperature range of 40°C is 113.5×20 m. The maximum of jet pressure and velocity of each section at the distance of 15-150 m from the nozzle is shown in *Table 3*, and the changes of pressure and temperature of the jet flow are shown in Figures 8-11. As the aircraft tested has a twin engine, the curve is distributed symmetrically, and half of the curves are presented in the figures. The distance between two engines is 6 m, and the midline of two nozzles is set as the origin of the x coordinate, so the pressure maximum appears in the position of 3 m in Figures 10 & 11.

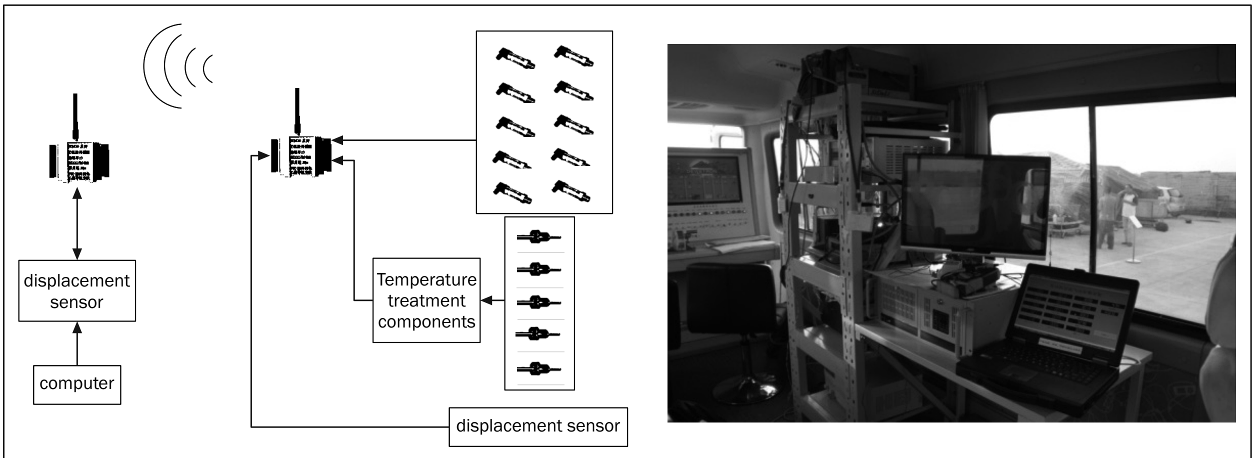

Figure 7 - The sensor signal procedure and the receiving device

Table 3 - Test results of jet flow centre

Number of test sections	1	2	3	4	5	6	7	8	9	10	11
Distances from tail of nozzle (m)	15	20	25	35	45	55	70	90	110	130	150
Maximum pressure (Pa)	9,600	5,600	4,170	3,200	1,940	1,420	940	720	400	981	58.8
Maximum temperature (°C)	160	117	106.3	88.5	84.3	69.1	66.3	46	43.5	38	30

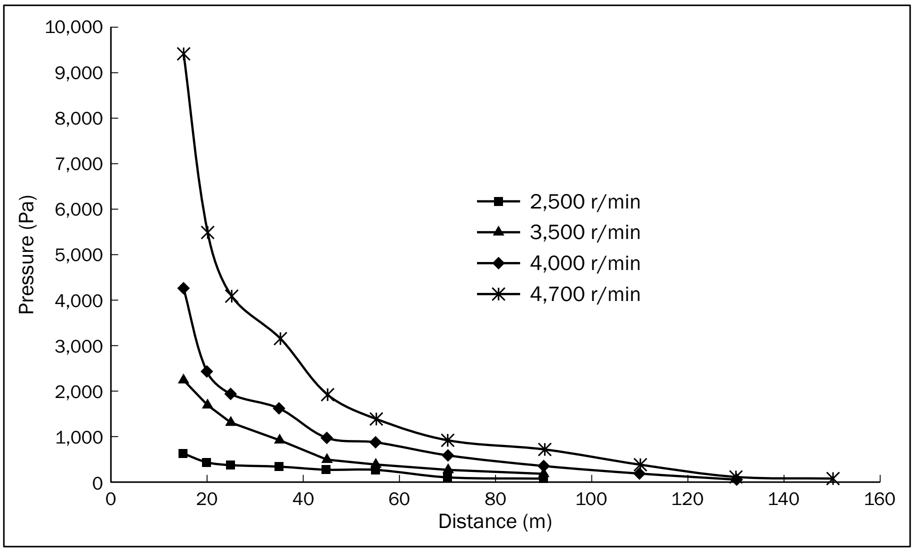

Figure 8 - Maximum pressure VS distance of longitudinal centre

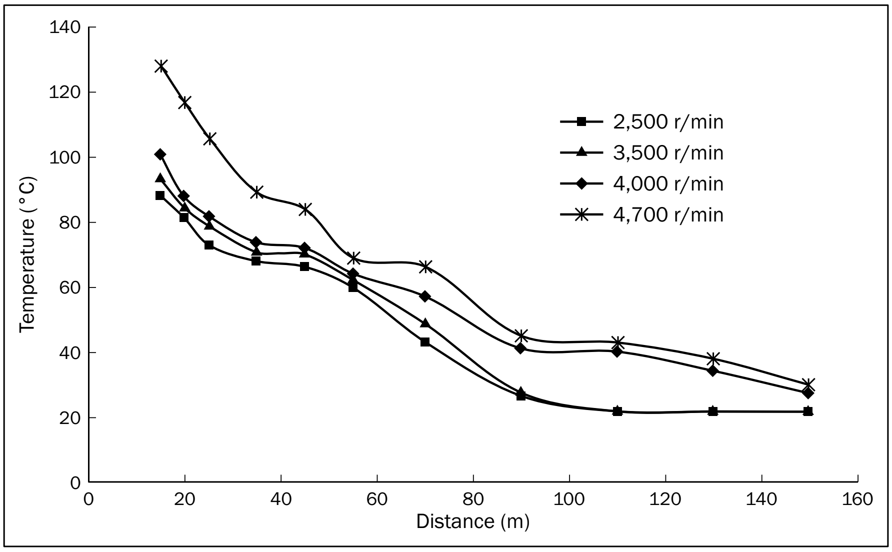

Figure 9 - Maximum temperature VS distance of longitudinal centre

From Figures 8-11 it can be concluded that:

(1) The pressure at the centre of the jet flow decreases gradually as the flow moves away from the nozzle, and its rate attenuates dramatically in the first 20 metres, reaching a maximum of 41.7%. The velocity at the centre of the jet flow gains disproportionately with the engine speed accelerating. The higher the engine speed, the greater is the augment rate of the pressure on the same measuring point, compared with the engine speed of the lower level.

(2) There is a clear boundary in the lateral direction of the flow and weak reverse flow appears around its edge. This entrainment is caused by a mixture of the boundary gas and air. In accordance with the jet theory, the jet flow of the nozzle in this paper diffuses toward both sides at an angle of 4° with the axis of the engine as its centre after leaving the nozzle. However, in the experiment, the data tested prove that the jet flow concentrates gradually towards the axis.

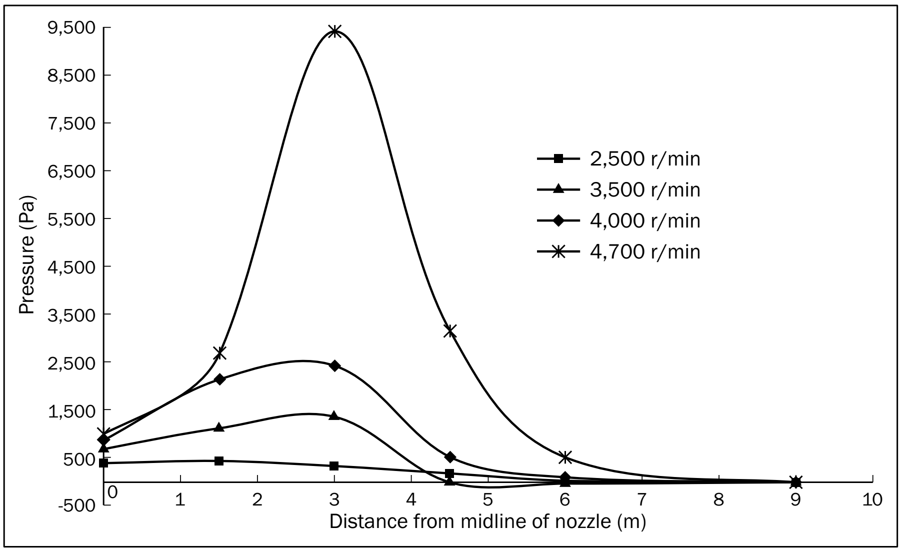

Figure 10 - Pressure distribution of test section (section 1 as an example)

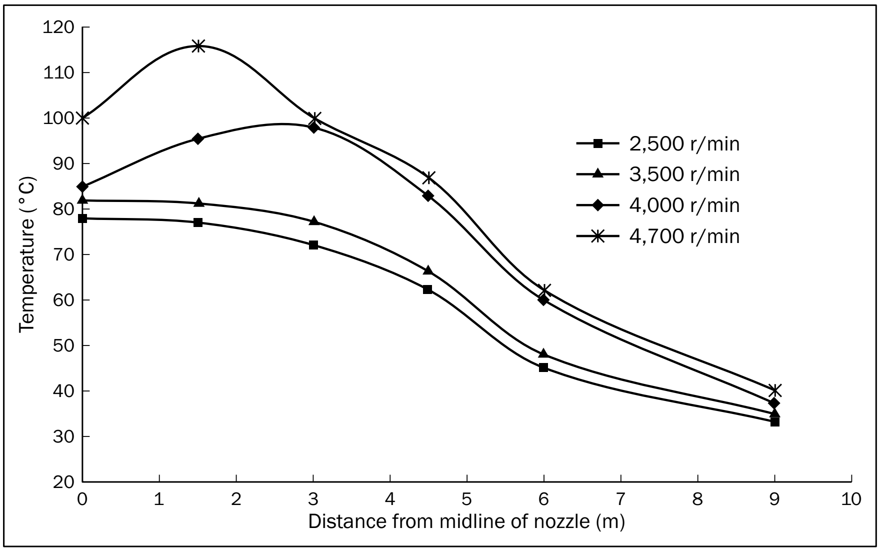

Figure 11 - Temperature distribution of test section (section 1 as an example)

(3) The temperature at the centre drops gradually as the flow moves farther away from the nozzle. The change is smooth, and the final temperature is nearly close to that of the atmosphere.

(4) The flows of two engines gradually mix after leaving the nozzles, and there is no superimposition between their temperatures and pressures.

4.2 Analysis of JBD tests

As the temperature of the jet flow falls fast, and the high temperature is less harmful than the high speed, the effect of the blast fence is only discussed in terms of the jet flow pressure.

When the blast fences are 25 m away from the nozzle, the pressure on section 2 (5 m in front of the fences) is shown in *Figure 12*, and that of section 4 (10 m behind the fences) is shown in *Figure 13*. When the blast fences are 35 m away from the nozzle, the test results of the two combined blast deflector fences with different heights are shown in *Table 4*. There is no big difference between the data tested on the sections behind the fences and only their maximum pressure along the axis of the engine is made for a comparative analysis.

Figure 12 shows the pressure distribution of the flow when it is 5 metres in front of the fences. It can be analyzed through the data that when the blast fence is installed (as shown in test plans B, C, D), the pressure becomes lower than it is when there is no fence (as shown in test plan A). This is because part of the reversed air in front of the fences offsets the jet flow. The highest pressure at the centre decreases by 13%, 1.4%, 11% and 12%, respectively in case of solid blast fence in test plan B, in louvered fence test in plan C, in the combined blast fences of 2 m in D1 and of 2.5 m in

Table 4 - Test results of combined blast fences (Pa)

Position	Plan	Section 2 (20 m)	Section 4 (35 m)	Section 5 (45 m)	Section 6 (55 m)	Section 7 (70 m)
25 m	plan D_1	941.760	2.943	0	0	9.620
	plan D_2	863.280	2.943	0	0	4.905
35 m	plan D_1	971.190	—	5.886	0	2.943
	plan D_2	981.000	—	5.886	0	2.943

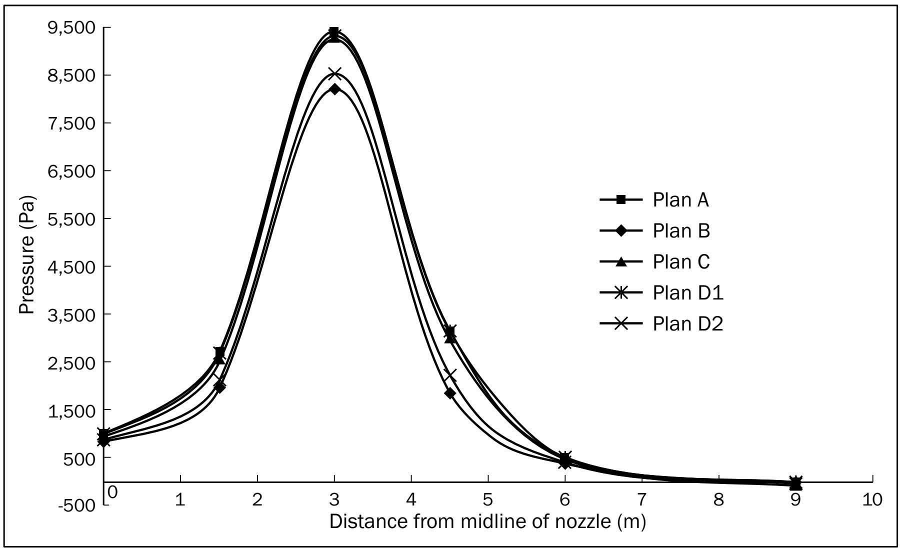

Figure 12 - Test results of section 2 (20 m)

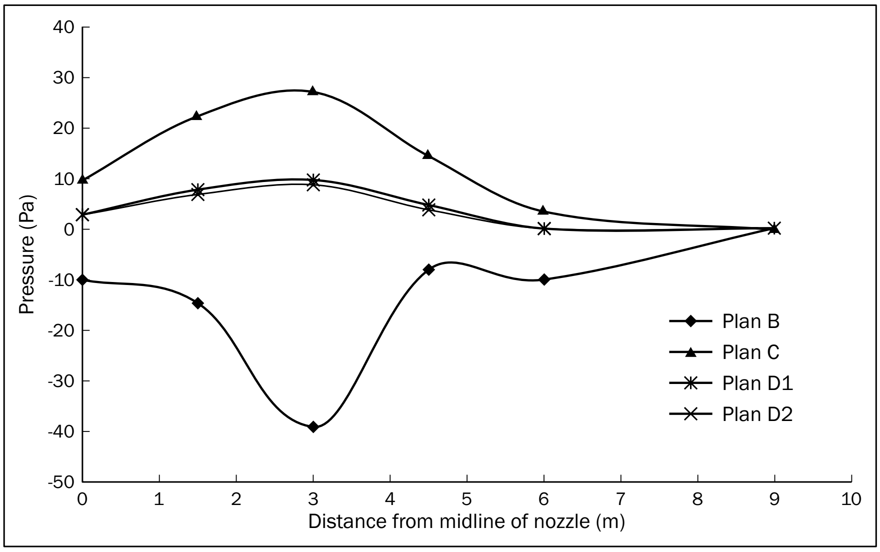

Figure 13 - Test results of section 4 (45 m)

D2. This illustrates that when the heights of all fences are the same, the volume of reversed air in front of the fences follows the order of the solid blast fence > combined blast fence > louvered blast fences, which indicates that the louvered blast fences play the best role in preventing the reversed air and that the higher the combined blast fence, the greater is the volume of the reversed air.

Figure 13 shows the pressure distribution of the flow when it is 10 m behind the fences. It can be seen that all the pressure drops below 40 Pa, which indicates that the fences reduce the harm of the jet flow. The negative pressure suggests the existence of an area of low pressure caused by the reversed turbulence behind the fences. The highest pressure of the reversed air could reach a maximum of 39.3 Pa, preventing both people and equipment from working normally. It can be analyzed through the data in *Figure 13* that the solid blast fence produces a relatively large reversed turbulence behind itself; the louvered one cannot fulfil the working requirements because the maximum pressure is 27.5 Pa, though there is no reversed turbulence. The combined blast fence solves the problem of the reversed turbulence and reduces the pressure to below 10 Pa, which is fit for work. This is because two parts of the combined blast fence are constructed according to a certain proportion and the reversed air caused by the solid part offsets the flow which passes through the louvered part.

As mentioned above, the combined blast fence not only reduces the jet flow in front of it but also compensates the deficiencies of too large turbulence behind the solid blast fence and too high pressure of the flow behind the louvered fence.

Data in *Table 4* show that the pressure of the combined blast fence is lower than 10 Pa when it is 10 m behind the fence, which is fit for work. The wind speed 20 m apart from the fence is 0; thus, it is not affected by the flow in front of the fence. The pressure of the flow increases when it is on section 7 (70 m), because the air flow deflected higher up in the air by the fence returns to ground due to the lower pressure in low altitude. Therefore, attention should be given to the aircraft which have high velocity at the initial stage and cause a zone of large negative pressure behind the blast fences.

The height of the blast fence is related to the position where it is set. It can be seen from *Table 4* that the closer the blast fence is to the nozzle, the higher is the fence. This is to ensure that the flow behind the fence will not drop due to the low pressure of the ground. Economically, when it gets farther apart from the nozzle, the height of the fence can be reduced because the flow attenuates itself a lot, and the height of the fence has little effect on the pressure of the flow.

5. CONCLUSION

This paper introduces the combined blast fence. It makes up for the deficiencies of the solid blast fence and the louvered one. Three conclusions are drawn as follows through the tests and research on the jet flow field and three types of blast fences.

(1) The movable measuring rake is designed to test the jet flow field and the blast fence. The results show that the testing system can meet the testing requirements, and the data is accurate.

(2) The pressure and temperature at the centre of the jet flow decrease gradually as the flow moves farther from the nozzle. They increase disproportionately with the rise in the engine speed. The pressure attenuates faster, reaching a maximum rate of 41.7%. The higher the engine speed, the greater is the augment rate of pressure on the same measuring point, compared with the engine speed of the lower level. The flow concentrates towards the axis of the nozzle in lateral direction.

(3) The combined blast fence not only reduces the pressure of the flow in front of it, but also solves the problems that the turbulence is too strong behind the solid blast fences and the pressure is too high behind the louvered blast fences. The height of the fence is related to the position where it is set: the nearer the fence is to the nozzle, the higher it is. When it is farther from the nozzle, its height can be lowered.

王海服 蔡良才 种小雷 耿昊
空军工程大学 机场机场建筑工程系 陕西 西安 710038

摘要

某型飞机尾喷气流流场及其导流设施试验研究

提出混合式导流屏弥补实体式和百叶式导流屏的不足，对飞机尾喷气流流场的和三种形式导流屏的2个距离6组试验进行分析。实验结果表明：飞机尾喷气流中心压力和温度随着与尾喷口距离的增大逐渐减小，压力衰减较快，衰减率最大达到41.7%，离喷口150m距离喷流压力最大可达58.8pa，相应风速为30m/s，一侧影响宽度最大可至22m，温度为40℃的范围可至距喷口113.5m的范围，一侧宽度为10m。混合式导流屏不仅使屏前流体压力降低，而且弥补了实体式导流屏屏后涡流过大和百叶式导流屏屏后气流压力过大的不足，屏后气流压力低于10pa。屏体的高度与导流屏设置的位置有关，距离尾喷口越近的位置，导流屏高度越高，；距离尾喷口越远，屏体高度可以减小。

关键词

尾喷气流；导流屏；试验研究；压力；温度；

REFERENCES

[1] Melbourne WH. Criteria for environmental wind conditions. J Wind Eng Ind Aerodyn. 1978;3(2-3):241–249.

[2] Durgin FH. Pedestrian level wind criteria using the equivalent average. J Wind Eng Ind Aerodyn. 1997;66(3):215-226.

[3] Bottema M. A method for optimisation of wind discomfort criteria. Build Environ. 2000;35:1-18.

[4] Willemsena E, Wisseb JA. Design for wind comfort in The Netherlands: Procedures, criteria and open research issues. J Wind Eng Ind Aerodyn. 2007;95:1541-1550.

[5] Janssen WD, Blocken B, van Hooff T. Pedestrian wind comfort around buildings: Comparison of wind comfort criteria based on whole-flow field data for a complex case study. Build Environ. 2013;59:547-562.

[6] Weng X, Cai L. Airport Pavement Design, 2th ed. [In Chinese]. Beijing: China Communication Press; 2007.

[7] Turnbull WJ, Foster CR. Effects of jet blast and fuel spillage on bituminous pavement. J Air Transp Division. 1957;83:71-81.

[8] Tucker TA. Meet USAF blast fence requirements. J Air Transp Division. 1959;85:1-26.

[9] U.S. Department of Transportation. Airport Design Advisory Circular. AC: 150/5300-13. Washington DC: Federal Aviation Administration; 2008.

[10] Kobayashi H, Schrader P, Sunohara Y, Harimoto K, et al. Experimental Study about the Wind Shielding Capabilities of Blast Fences. J Wind Eng. 2000;83:161-173.

[11] Wang Haifu, Cao Sijie, Chong Xiaolei, et al. Numerical Simulation of Different Blast Fence Forms Effect on Jet Flow Field [In Chinese]. J Airf Eng U (Nat. Sci. Ed.). 2012; 13(2):16-19.

[12] Wang Haifu, Cai Liangcai, Chong Xiaolei, et al. Plane Dimension Design of Composite Flow Guiding screen [In Chinese]. Archit Technol. 2010; 41(11):1057-1058.

[13] Jie Lin. Study of Characteristic for Nozzle Flow Field of Aircraft Engine [PhD thesis]. Xian: Air Force Engineering University; 2012.