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EFFECT OF SHUTTER GEOMETRY ON THE FREE CONVECTION FLOW THROUGH THE WINDOW

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تأثير الشكل الهندسي للشيش على سريان الحمل الحراري خلال النافذة

خلاصة - يهدف هذا البحث المعملي إلى دراسة تأثير الشكل الهندسي لشيش النافذة على الحمل الحراري خلاله . ولهذا السبب تم إنشاء جهاز معملي يمكن بواسطتة قياس التغيرات في درجات الحرارة على جانبي قطاع إختبار مماثل لشيش شباك حقيقي تحت ظروف هندسية مختلفة . وقد إستخدم سخان كهربي لتسخين الفراغ على أحد جانبي قطاع الإختبار بينما ظل الجانب الأخر بدون تسخين . وقد تم إختبار تأثير كل من زاوية الشيش والنسبة بين عرض الشيشة والمسافة البينية على توزيع درجات الحرارة . الشيش المثالي هو الذي يعمل كما لو كان ديود حراري أي يسمح لسريان الحمل الحراري فقط في إتجاه واحد . إن قدرة الشيش على مقاومة سريان الحمل الحراري في إتجاه معين تزداد بزيادة كل من زاوية الشيش ونسبة عرض الشيشة والمسافة البينية . فقد أظهرت النتائج التي عرضت بصورة بيانية أن زاوية الشيش يجب أن تزيد عن ٤٥ درجة وأن النسبة بين عرض الشيشة والمسافة البينية يجب أن تكون أكبر من ٤ للحصول على أداء جيد للشيش .

ABSTRACT - The objective of this experimental work is to study the effect of the shutter geometry on the free convection flow of warm air through the window. For this purpose, a setup is fabricated to measure the temperature variations on both sides of a test section, which is similar to a real shutter, under different geometrical conditions. The space of one side is heated by a hot plate, while the other is kept unheated. The effect of the shutter angle and aspect ratio on the temperature distribution on both sides has been examined. Ideal shutter is the one which acts as a thermal diode, by allowing the free convection flow of warm air only in one direction. The ability of the shutter to resist the free convection flow of warm air through the window, in a certain direction, increases by increasing the shutter angle and aspect ratio. Results which are given in graphical form, have shown that the shutter angle and aspect ratio should be more than 45° and 4 respectively, to obtain a good performance.

INTRODUCTION

Energy conservation in the buildings is essential to overcome the present shortage in the conventional sources of energy. One way to approach this is to minimize both the Winter space heating and the Summer air conditioning loads. The window movable shutters are used in Egypt from long ago to perform this. The direction of the shutter angle can be reversed, to minimize the free convection of warm air from outside in the hot Summer, and keep the heat losses from inside at a very low level in the Winter. Besides the shutter angle, the breadth of the shutter slices, and the spacing between them are seen to be the most significant parameters that affect the free convection through the shutter. In fact, this is a natural convection problem through a vertical cascade of inclined parallel plates. According to the knowledge of the authors, there is no available data handling this problem. This may be due to the complex or uncertain boundary conditions involved. However, the horizontal cascade of vertical parallel plates has been studied in [1,2]. Results of these researches have been used in cooling the electronic equipments.

The shutter can act as a thermal diode under some operating and geometrical conditions. The free convection flow of warm air through the shutter depends on both the driving force, and the flow resistance offered by the shutter. The driving force is created by the air temperature (and hence the density) difference between both sides of the shutter. The resulting pressure head forces the warm air to flow through the window from the hot side to the cooler. The free convection flow of warm air is only upwards. Therefore, if the shutter slices are directed such that the warm air has to flow downwards, the shutter in this case acts as a resistance to the flow. In the ultimate case, the flow will be stopped if at least this resistance is equal to the driving force. However, the problem is not so simple since the driving force is not only a function of the air temperatures in both sides of the shutter. It depends also on the inner pressure head, created by the window elevation from the room floor. This head may be negative, zero or positive with respect to that of outside, according to the room temperature distribution in the vertical direction. Therefore,this pressure head my be added to the driving force to overcome the shutter resistance, or subtracted from it to reduce the flow rate. These situations are difficult to be defined. The existence of free convection currents near the shutter may also affect the net flow rate through the window.

Some designs of the thermal diode are available [3,4]. But none of them can be used in the buildings due to the technical, architecture and economical problems that may be involved. The most suitable thermal diode for domestic use is the ordinary shutter, if it is well designed. Besides its thermal diode action, it is also essential for the fresh air circulation in the room. Figure 1 shows a demonstration of the shutter performance in both the Winter and Summer seasons. In the Winter, the direction of warm air flow should be only from outside to the room, provided that the outside air temperature is higher than that of the room. In the Summer, the direction of warm air flow must be reversed. The same shutter can perform these two situations by reversing the direction of the shutter angle as shown in the figure.

EXPERIMENTAL SETUP AND PROCEDURE

The setup consists of a horizontal duct, connected from one end to a vertical duct as shown in Fig. 2. The two ducts are made from wood, and the connection between them is air sealed.The inner cross section of each duct is a square 18x18 cm, and the thickness of its wall is 2 cm. Four test sections are made: each one is a square wooden frame 18x18 cm from outside. The frame sides have a thickness of 2 cm. and a width of 3 cm. and can be fixed with some fit inside the horizontal duct at the connection joint as shown in Fig. 2. The vertical sides of each frame have inclined slots from inside. Each slot is 1 cm deep and has a sufficient width to hold a Formica sheet with little fit. The perpendicular distances between slots are equal for all test sections (8 mm.). The slot (shutter) angle θ, is varied from one frame to the other. It takes the values 15°, 30°, 45° and 60° in the four test sections.

Formica slices are prepared, with a suitable length to be easily fixed between the opposite slots. The slices are divided into four groups with different breadths; namely 16, 32, 48 and 64 mm. These dimensions are chosen to be multiples of the slices spacing. The setup is fixed with wooden legs to keep the lower end of the vertical duct about 1 cm above the ground. This is to allow the fresh ambient air to get inside the duct. An electrical hot plate (120 Watts) is used to heat this air and the space inside the vertical duct. The setup is suitably instrumented with 11 Copper-Constantan thermocouples to measure the temperature distribution along the horizontal duct center line, and on its extension in the vertical duct. The thermocouples are fixed 8 cm. apart, and the test section is exactly fixed at the mid point between the thermocouples number 3 and 4 as shown in Fig. 2.

The shutter angle, slices breadth and the spacing between them are to be changed for examining their effect on the shutter performance. Therefore, it was necessary to eliminate the effect of any other parameters. In fact, the flow area across the test section is only the major parameter that may be affected by changing the shutter angle θ. A part of the area with a height h is closed by the lower slice as shown in Fig. 2. From the system geometry,

$$h = B \tan \theta$$

Where, B is the width of the frame (B = 3 cm.).
The maximum angle has been tested is 60°. Therefore, all the test sections are partially closed from below with Formica strips of height 3 tan 60 = 5.2 cm. By this way, the shutter vertical flow area is kept the same for all test sections, irrespective of the value of shutter angle. However, with constant value of the perpendicular spacing, the number of slices increases by decreasing the shutter angle. In our case, the number of slices are: 7, 11, 14 and 17 corresponding to the shutter angles 60°, 45°, 30° and 15° respectively. The influence on the flow area is very little, since the Formica sheet thickness is only about 0.4 mm.

The experiments are divided into four groups by replacing the test section (i.e. changing the shutter angle) in each one. Four experiments are conducted for each group corresponding to the slices breadths 16, 32, 48 and 64 mm. A preliminary experiment was carried out with an empty frame (no slices) for the purpose of comparison. At the beginning of each experiment, the hot plate is switched on, and then the temperatures are recorded at different points, for 90 minutes, with time intervals of 15 minutes. The ambient air temperature is also recorded.

RESULTS AND DISCUSSION

In fact the measurement of the free convection flow in our case is not an easy task. The temperature distribution along the flow direction is seen to be a good indicator to the flow of warm air across the test section, provided that the ambient air temperature is kept constant. But the later changes with time, and from experiment to another. Accordingly, the thermal losses to the ambient air may affect the comparison process. Therefore, to minimize the effect of thermal losses in all experiments, the temperature rise at any point (above that of ambient air) is considered. Since the aim of this work is only the comparison between the performance of different test section configurations, the temperature distribution along the horizontal duct center line is seen to be sufficient for this purpose. On the other hand, The geometrical parameters can be reduced to the shutter angle and the aspect ratio, where the latter is defined by,

Shutter aspect ratio = Slice breadth / Perpendicular spacing.

This is more convenient in representation of the results.

Figure 3 shows the results with no slices fixed in the test section. The temperature rise along the flow direction after 15, 30, 45, 60, 75, and 90 minutes from the beginning of the experiment, is given in Fig. 3.a. The distance on the horizontal axis is measured from the location of the thermocouple number 1. It is clear that the temperature distribution lines are getting more crowded with the time. This is due to transient period that follows the switching on the hot plate. However, the steady state is approached after about 90 minutes as shown clearly in Fig. 3.b. This fact is true for all the other experiments. Therefore, all the experiments are terminated after 90 minutes.

The results with slices fixed in the test section are given in the Figures from 4 to 7. The temperature rise variations with time for the shutter angles 15°, 30°, 45° and 60° are depicted in Figures 4, 5, 6 and 7 respectively. The results for different aspect ratios 2,4,6 and 8 are shown as a, b, c and d respectively in the same figures. In general, the drop in the temperature level downstream the test section can be observed. This drop is more clearly observed for higher aspect ratios with the shutter angle 15° as shown in Fig. 4. For the same aspect ratio, this trend is more pronounced for larger shutter angles as shown in Figures 5, 6 and 7. On the other (heated) side of the test section, there is a slight increase in the temperature level with the increase in both the shutter angle and aspect ratio. Therefore, a sharp drop in the temperature level across the test section can be seen in Fig. 7.d where the shutter angle is 60° and the aspect ratio is 8.

In order to emphasis the effect of the shutter angle and aspect ratio on the temperature levels on both sides of the shutter, the temperature drop across the test section in all cases is shown in Figures 8 and 9. The effect of the shutter angle for different aspect ratios is shown in Fig. 8, while the effect of aspect ratio for different shutter angles is given in Fig. 9. The temperature drop in these figures is the difference between the average temperature levels on both sides of the test section. The maximum value of the temperature drop (represented by solid lines) occurs between 30 and 45 minutes. On the same figures, the mean value over the 90 minutes is also shown by dotted lines. In general, the temperature drop across the test section increases with the increase in both the shutter angle and aspect ratio. This effect is seen to be more pronounced when the shutter angle and aspect ratio are larger than 45°and 4 respectively as shown in Figures 8 and 9. However, the temperature drop can reach a value of 13.6°C with the shutter angle 60° and aspect ratio 8. comparing this value with that of empty frame (6.3°C), an increase in the temperature drop of 7.3°C is occurred due to the existence of the shutter. By the language of energy conservation, this amount has a considerable effect on the space heating and cooling loads.

CONCLUSION

The effect of shutter geometry on the free convection flow of warm air through the window has been experimentally tested. The temperature variations on both sides of a test section, similar to a real shutter, are recorded for different geometrical conditions. The space of one side is heated by a hot plate, while the other is kept unheated. The effect of shutter angle and aspect ratio on the temperature distribution on both sides has been examined. It was found that the ability of the shutter to resist the free convection flow of warm air through the window, in a certain direction, increases by increasing the shutter angle and aspect ratio. Results, which are given in graphical form, have shown that the shutter angle and aspect ratio should be more than 45°and 4 respectively, to obtain a good performance. The well designed shutter can approach the thermal diode, by allowing the warm air to flow inside the room in Winter and reverse the process in Summer. More future study on an actual system is recommended.

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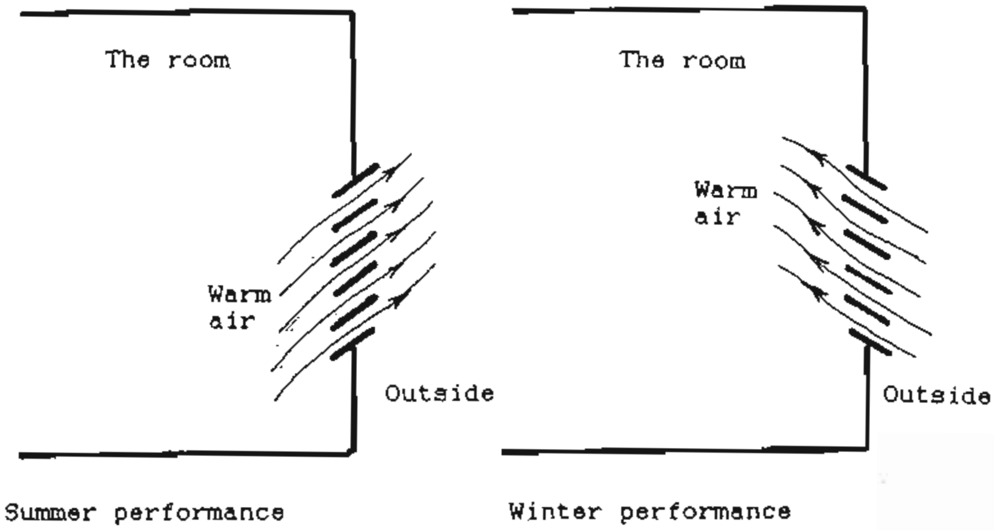

Fig. 1. Performance of the shutter in both the Summer and Winter seasons.

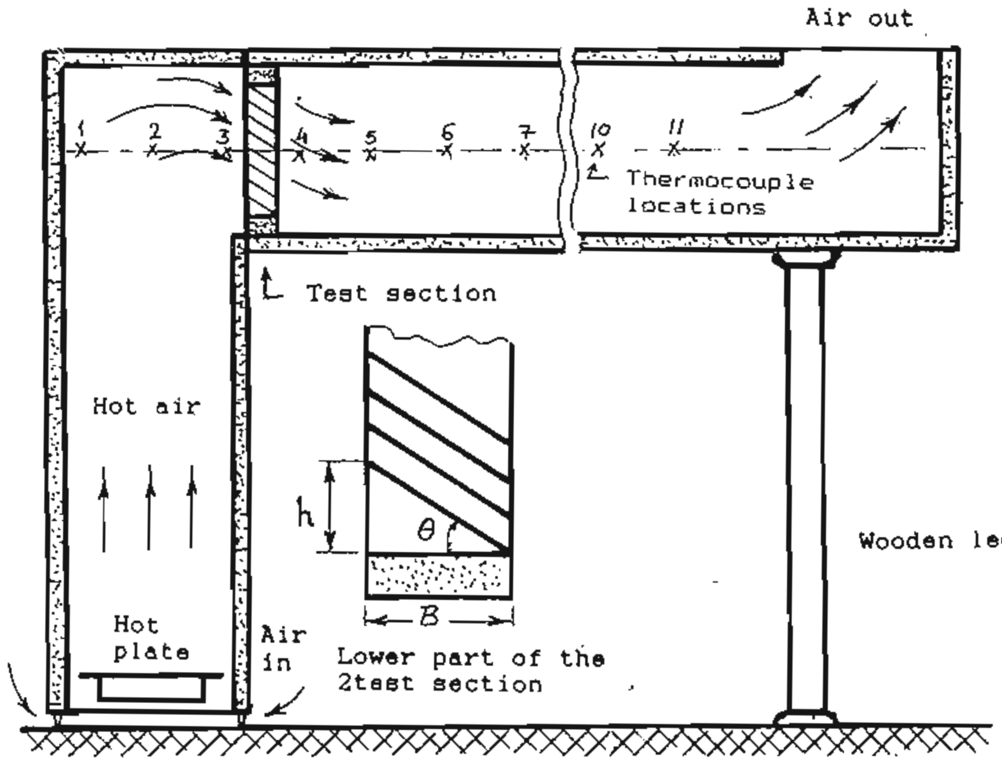

Fig. 2. A sectional view of the setup showing the flow of hot air through the test section.

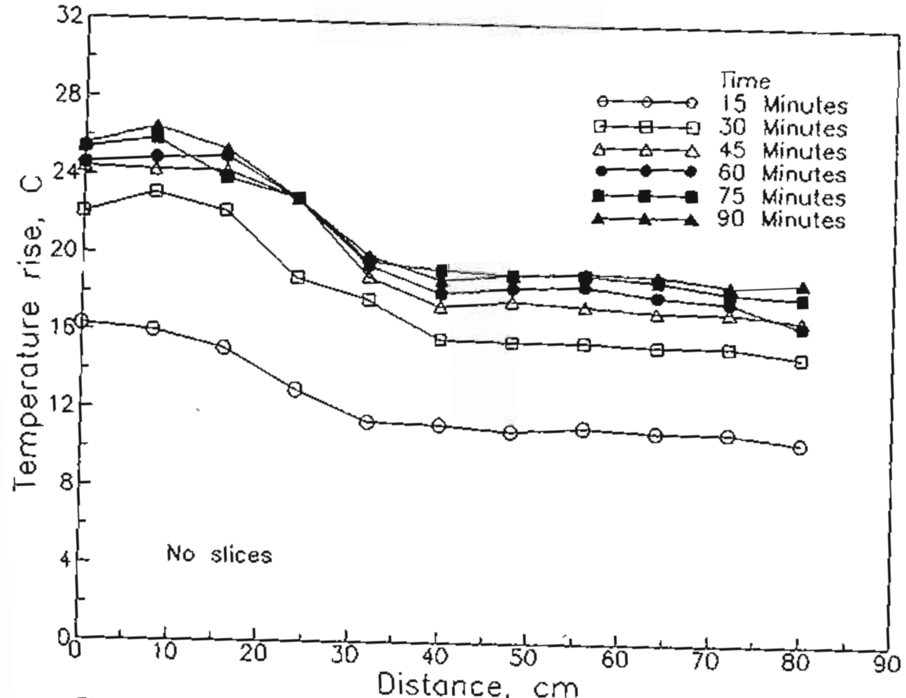

Fig. 3.a Temperature rise along the horizontal duct center line.

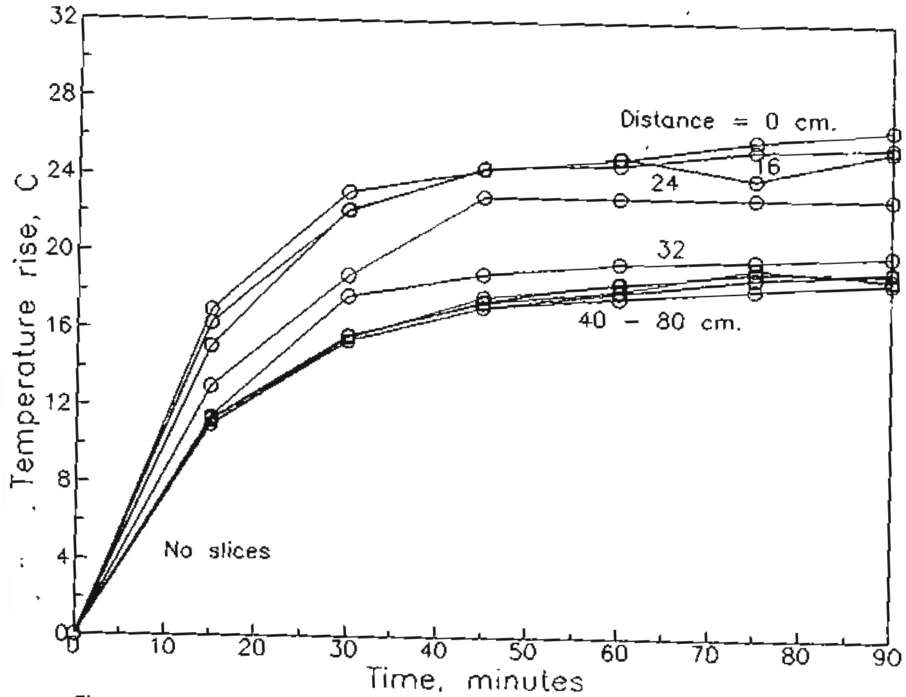

Fig. 3.b. Temperature rise with time at different locations on the horizontal duct center line.

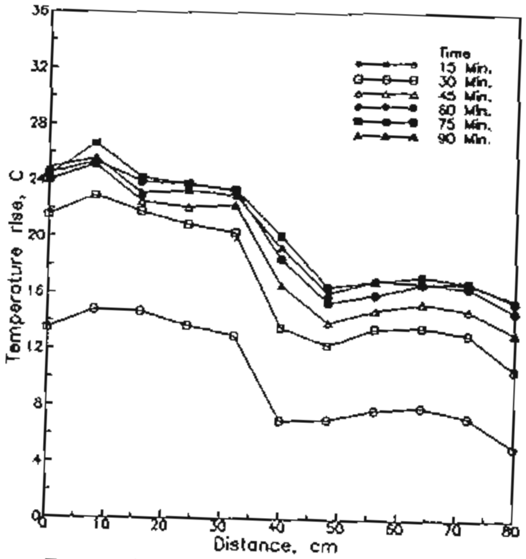

Fig. 4.a Temperature rise along the horizontal duct center line at different times. Shutter angle = 15 degrees Aspect ratio = 2

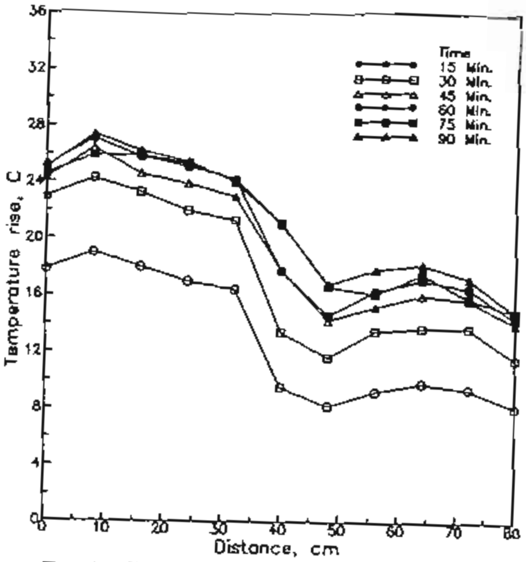

Fig. 4.b Temperature rise along the horizontal duct center line at different times. Shutter angle = 15 degrees Aspect ratio = 4

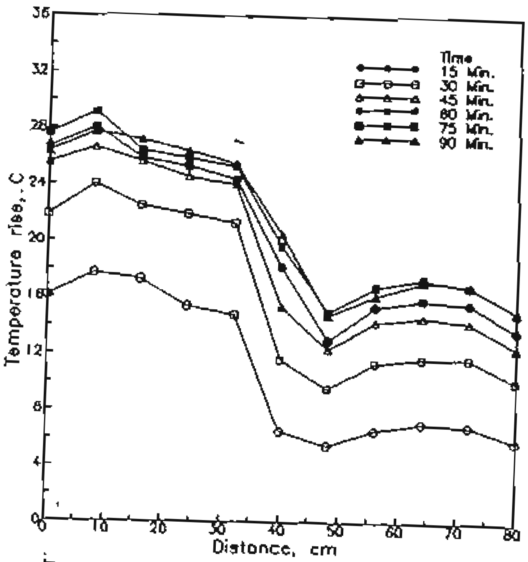

Fig. 4.c Temperature rise along the horizontal duct center line at different times. Shutter angle = 15 degrees Aspect ratio = 6

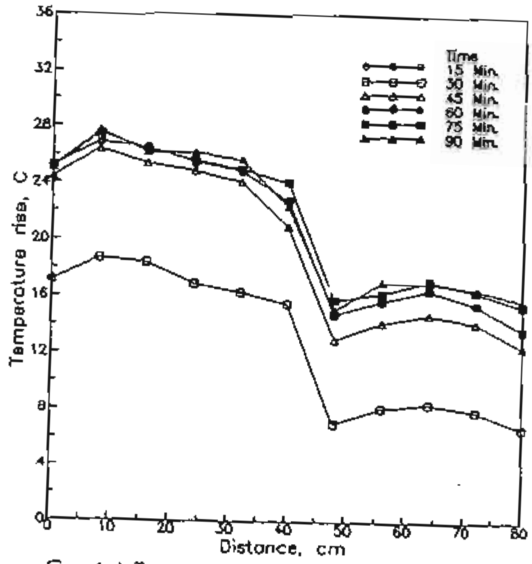

Fig. 4.d Temperature rise along the horizontal duct center line at different times. Shutter angle = 15 degrees Aspect ratio = 8

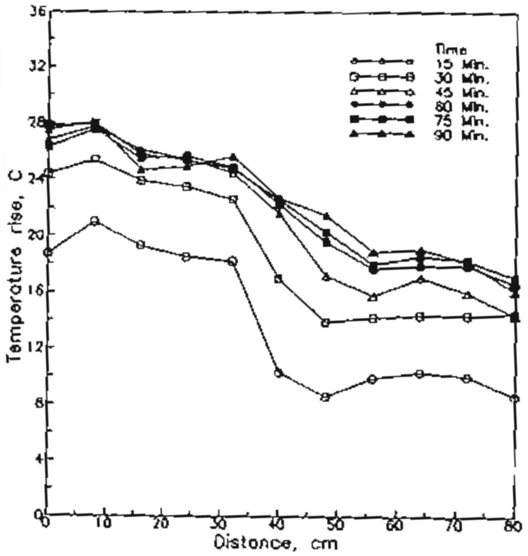

Fig. 5.a Temperature rise along the horizontal duct center line at different times.
Shutter angle = 30 degrees
Aspect ratio = 2

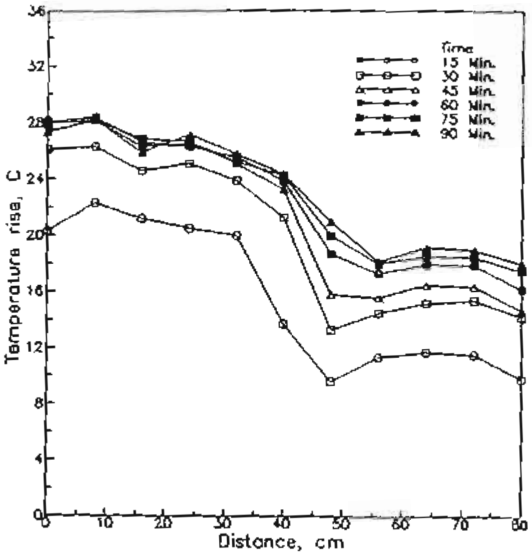

Fig. 5.b Temperature rise along the horizontal duct center line at different times.
Shutter angle = 30 degrees
Aspect ratio = 4

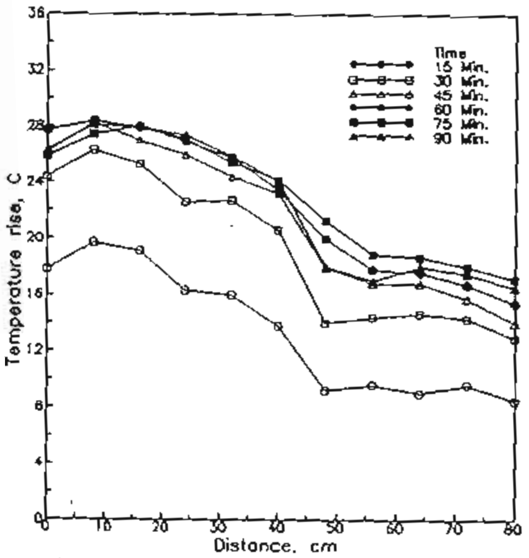

Fig. 5.c Temperature rise along the horizontal duct center line at different times.
Shutter angle = 30 degrees
Aspect ratio = 6

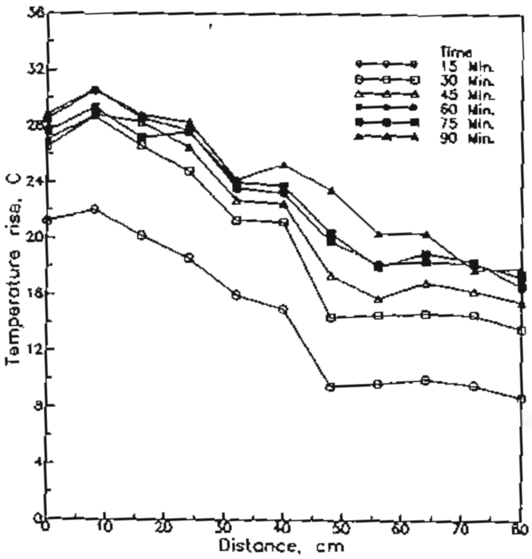

Fig. 5.d Temperature rise along the horizontal duct center line at different times.
Shutter angle = 30 degrees
Aspect ratio = 8

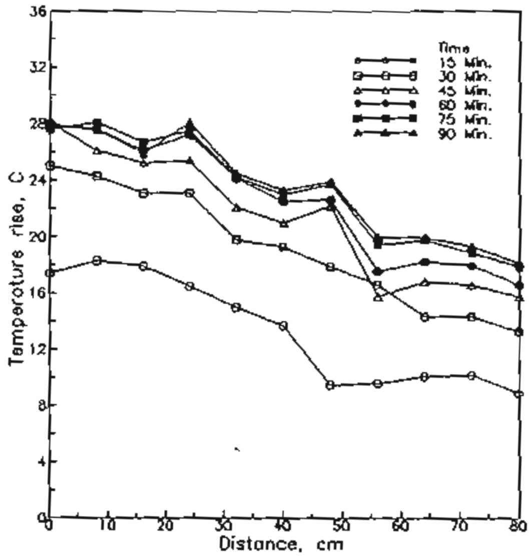

Fig. 6.a Temperature rise along the horizontal duct center line at different times.
Shutter angle = 45 degrees
Aspect ratio = 2

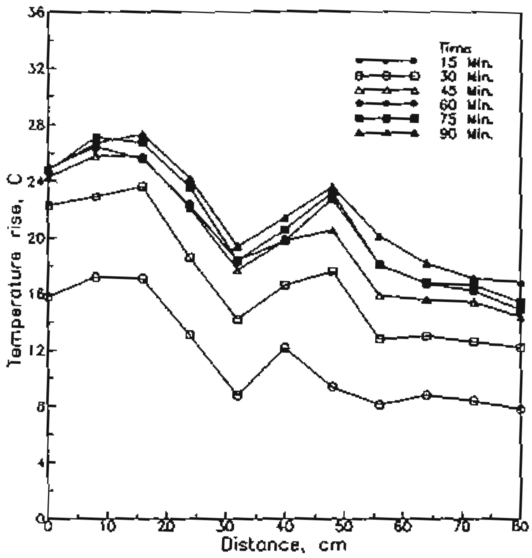

Fig. 6.b Temperature rise along the horizontal duct center line at different times.
Shutter angle = 45 degrees
Aspect ratio = 4

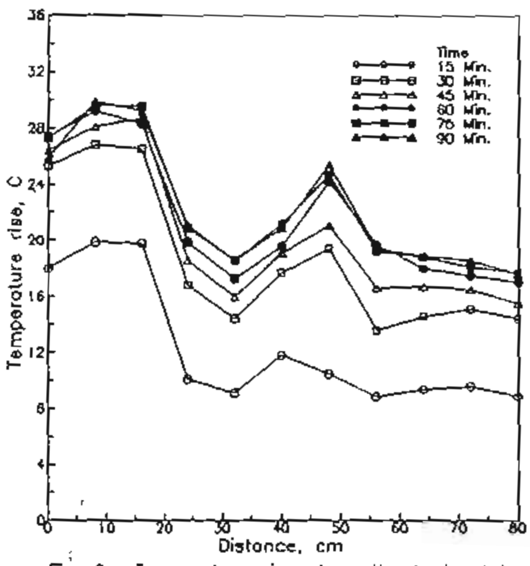

Fig. 6.c Temperature rise along the horizontal duct center line at different times.
Shutter angle = 45 degrees
Aspect ratio = 6

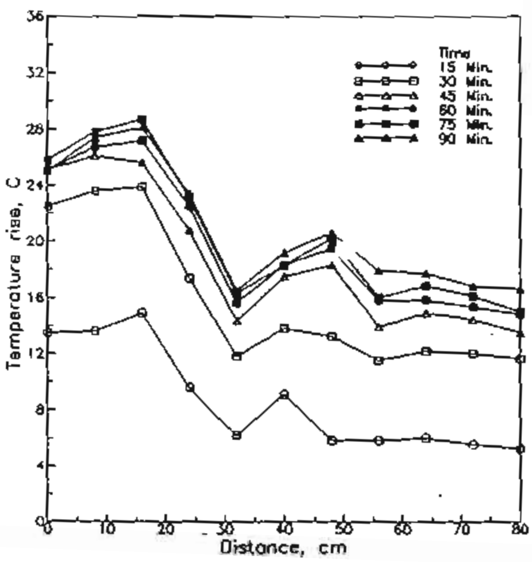

Fig. 6.d Temperature rise along the horizontal duct center line at different times.
Shutter angle = 45 degrees
Aspect ratio = 8

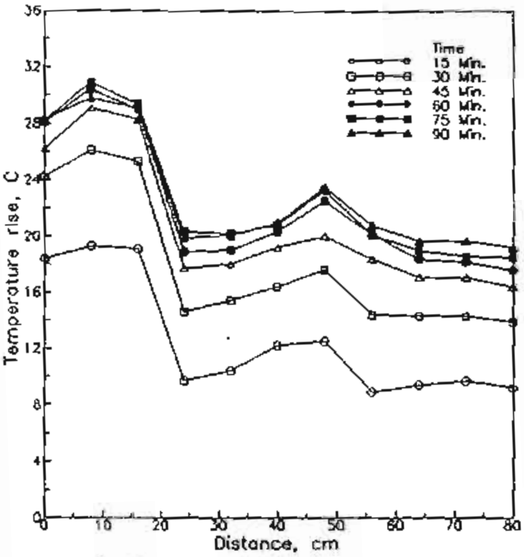

Fig. 7.a Temperature rise along the horizontal duct center line at different times.
Shutter angle = 60 degrees
Aspect ratio = 2

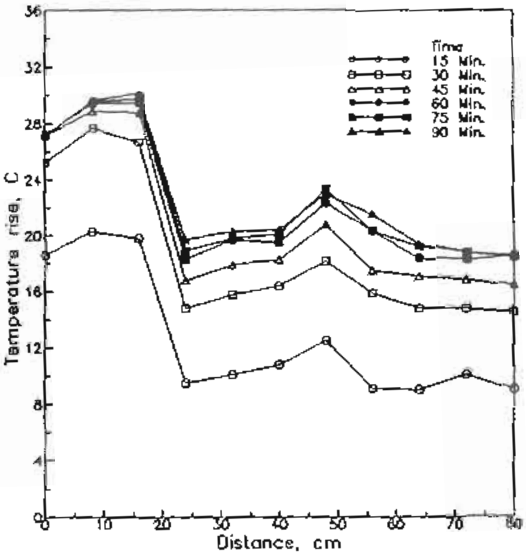

Fig. 7.b Temperature rise along the horizontal duct center line at different times.
Shutter angle = 60 degrees
Aspect ratio = 4

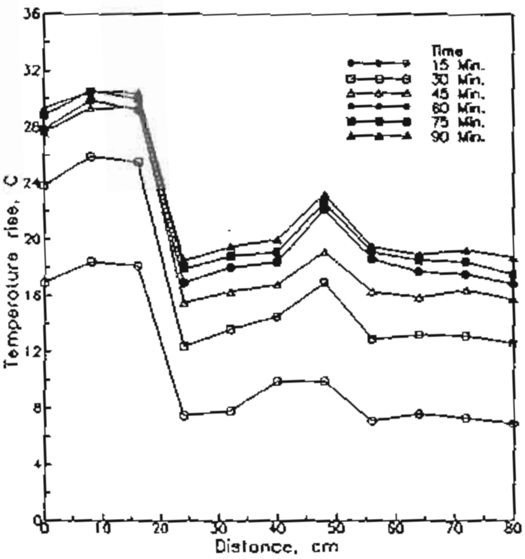

Fig. 7.c Temperature rise along the horizontal duct center line at different times.
Shutter angle = 60 degrees
Aspect ratio = 6

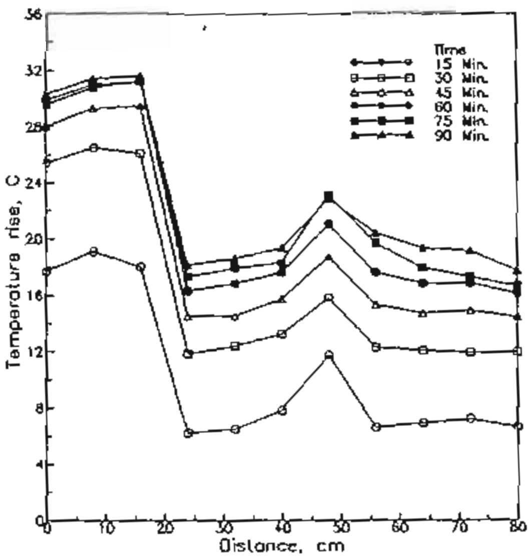

Fig. 7.d Temperature rise along the horizontal duct center line at different times.
Shutter angle = 60 degrees
Aspect ratio = 8

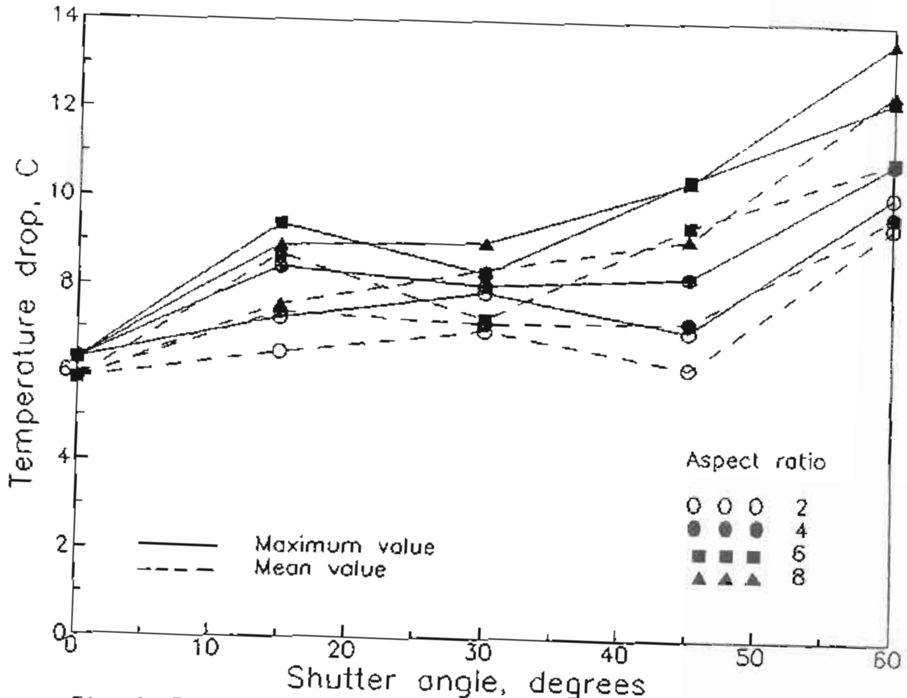

Fig. 8. Effect of the shutter angle on the temperature drop between both sides of the test section.

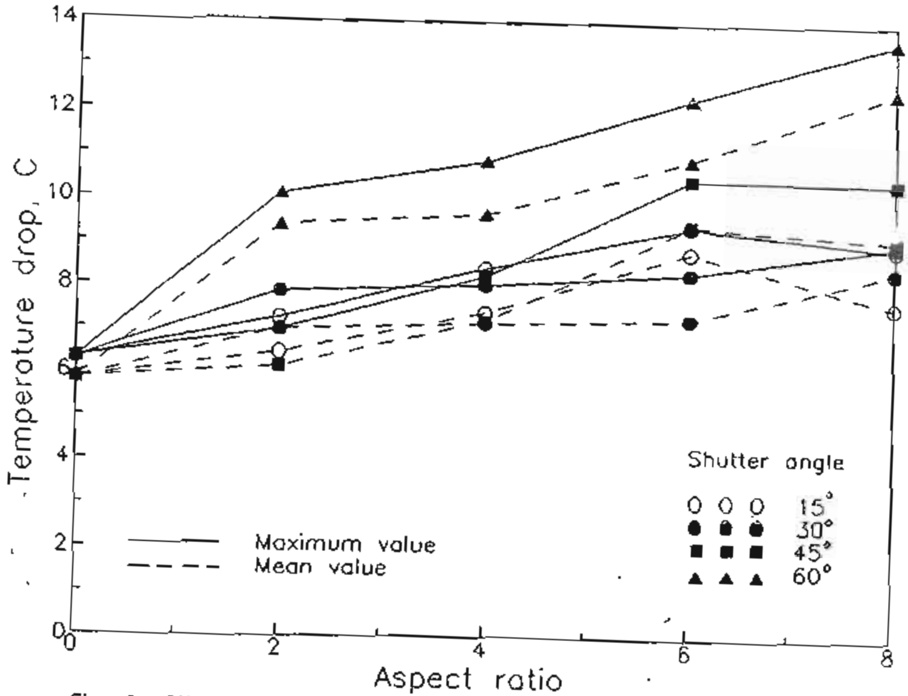

Fig. 9. Effect of the aspect ratio on the temperature drop between both sides of the test section.