HIGH SPEED FLOW THROUGH A SUDDEN EXPANSION DUCT MOUNTED BLUFF BODIES

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Abstract

An experimental investigation of high speed flow through an axisymmetric enlarged duct mounted rectangular annular ribs on the inner surface was performed. These ribs were used to create secondary vortices inside the duct which are useful for the enhancement of mixing process. The effect of these vortices on the base pressure as well as the base drag are also useful in many flight configurations. The high speed flow was generated by a convergent nozzle with the range of stagnation pressure from 1.29 to 2.67 atmospheres. Results show that the main behavior of the flow pattern is the same as that of the duct without ribs. The development of the pressure field is faster for the case of ducts with ribs. The ribs height has a great influence on the pressure field. The degree of influence increases with ribs height as well as the stagnation pressure.

Nomenclature

AR : Area ratio
d : Exit nozzle diameter
D : Duct diameter
p_a : Ambient pressure
p_b : Base pressure
p_o : stagnation pressure

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L : Duct length
M : Mach number
NR : Ducts without ribs
RS : Aspect ratio = RH/RW
p_w : wall pressure
RH : Ribs height
RW : Ribs width

Introduction

Supersonic mixing in many applications may directly benefit from further understanding the flow behind an axisymmetric rearward facing step in supersonic flows. Such applications in modern gas turbine combustion chambers require that the combustor must burn fuel completely. In recent years, the integral rocket ramjet has emerged as a new air breathing system. The basic ramjet combustor configuration is known as a sudden expansion dump type combustor. In such systems, fuel injection occurs in the air inlet duct upstream of the dump station. Primary flame stabilization is provided by flow recirculation just downstream of the sudden expansion. The high turbulent intensities in this region increases the mixing process between the fuel and air and hence, enhances the combustion process.

The flow field associated with an abrupt increase in cross sectional area is a complex phenomenon characterized by flow separation, flow recirculation and flow reattachment. In high speed flows (supersonic case), the flow field turns in the direction of the abrupt change area through on expansion fan, with a resulting mixing layer between the supersonic fluid above and the subsonic recalculating region below, Fig.1a. The pressure in the recirculation zone is known as the base pressure and the associated flow field is known as the base flow. Such a flow field was found to be affected by inlet flow conditions (p_o, M), initial boundary layer thickness, area ratio, and the duct length to diameter ratio, Korst (1956). The study of base pressure is important in the aerodynamic design of various flight configurations. The increase in the base pressure results a decrease in the pressure drag. The details of the base flow have been studied by several authors. At first, the flow at the base portion is determined by a strong interaction between the viscous recalculating region at the base portion and the external inviscid flow, Chapman-Korst flow model, Korst (1956). Recent studies concerning the flow field and base pressure have been reported by chow (1959), McDonald (1966), Donaldson (1967), Scherberg and Smith (1967) and Jakubowski and Lewis (1973).

Over the years, many attempts have been made to increase the burning efficiency of fuel burners and combustors and reduce the base drag in most of the flight configurations. Many of these systems employ the central recirculation zone generated by a strong swirling flow in order to enhance the flame stability and mixing process. This type of flow is also seen in the short length diffusers and piping systems. A co-axial swirling jet was also used by many researchers to control the mixing process and flame stabilization, Khalil (1978). In fact, swirl sets up the radial and axial pressure gradient which contribute to the formation of central recirculation zones and may lead to vortex breakdown phenomena. Habib and WhiteLaw (1980) measured velocity and turbulence intensity distributions for a co-axial swirling jet exhausting into a suddenly expanded confinement. Ishikawa (1983) made an attempt to study the gas motion in the early mixing region of a model secondary combustor of a rocket/ramjet and examined the mixing process and behavior of a recirculation flow for the case with and without a bluff body. Such a passive control was pair of ribs of different sizes installed at the upstream end of the mixing chamber. Results show that such a bluff body affected the behavior of the flow field and mixing process. This is because the recirculation flow and pressure gradient were affected by these ribs. In fact, ribs have also been used in many other engineering applications such as hypersonic aircrafts, Youn et al (1994) and Acharya et al (1994). This is to increase the heat transfer in turbulent duct flows by increasing the heat transfer area and by disturbing the laminar sublayer.

The present study describes a sudden expansion high speed flow through an axisymmetric duct in which circular bluff bodies (passive control concept) were mounted, Fig. 1b. The bluff bodies were annular ribs of rectangular cross section. These ribs were installed along the duct length. The passive control concept has been studied by many researchers as an economical method to improve the performance of many engineering devices. The purpose of providing these ribs is to create secondary vortices in the duct in order to enhance the mixing process. Here, the main objective is to study the effect of such secondary vortices on the flow field and pressure development along the duct wall. The influence of these vortices on the base pressure at the recirculation zone is also studied. Measurements were made at different stagnation pressure ratios, different values of the rib height and duct length to diameter ratios. The pressure field was characterized via the base and wall pressure measurements.

Experimental set up and procedure

The experiments were conducted with a high speed wind tunnel facility, Fig. 2. Compressed dry air was supplied by a compressor to a large tank which eliminated any variation in the flow rate. The air flow rate was controlled by the gate and pressure regulating valves. The air then was flowed into a settling chamber. Screens were placed into the settling chamber to reduce the air disturbances at the nozzle inlet. The air was then accelerated through an axisymmetric convergent nozzle. The exit diameter of the nozzle was 10 mm. The nozzle directed the flow horizontally into an axisymmetric enlarged duct with an inner diameter (D) of 25 mm. Thus, the area ratio (the ratio between the area of the duct to that of the nozzle exit) was fixed at 6.25. The air from the enlarged duct was exhausted into the ambient atmosphere. Two models of the enlarged duct, with and without bluff bodies were tested. The bluff bodies used were annular ribs of rectangular cross section which were made on the inner surface of the duct. The width of ribs (RW) was 3 mm and the height (RH) was varied as 1, 2 and 3 mm. Therefore, the aspect ratio (RS) of ribs was varied as 1/3, 2/3 and 3/3. The first rib was installed at a distance of 25 mm from the nozzle exit plane and the other were setted behind the first one with an interval space of D/2. The duct length (L) was varied from 25 mm to 150 mm.

Measurements of base and wall pressures were made for different values of tested parameters. The base pressure was measured via a pressure tap at the mid point of the base portion in the sudden expansion zone, Fig. 1a and Fig. 2. Whereas, pressure taps of 1 mm inner diameter were made along the duct length for measuring the wall pressure. These taps were distribution along the duct length with 6 mm abart starting from the duct inlet. At first, the flow test was made on the duct of L = 150 mm. Therefore, these taps were located at follows:

$\frac{x}{L}$	0.04	0.08	0.12	0.16	0.2	0.24	...

from the beginning of the enlarged duct. Then the duct length was reduced to change L/D ratio. Thus, the number of pressure taps was reduced to be one tap at x/L = 0.24 for the duct length of 25 mm. A pitot tube was supported by a traversing system placed just at the duct exit. The pitot was used to measure the total pressure at the axis of the enlarged duct. The pressure readings were collected with the help of U-tube mercury manometers. All measurements were made for a wide range of stagnation pressure from 1.2 to 2.6 atmospheres. Therefore, subsonic and supersonic underexpanded jets were expanded through the enlarged duct. The stagnation temperature in the settling chamber was uniform at 30 ± 1 C^o and the room temperature was uniform at 27 ± 1 C^o. The measured values of total and static pressures were repeatable within ± 3 %. The length and diameter of the duct were used as a length scale for normalization.

Results and Discussion

Figure 3 shows the variation of the base pressure with L/D ratio for the duct with and without ribs. This variation is uniform for the ducts without ribs. It decreases as the tube length is increased. For ducts with ribs (RS=1/3), the effect of ribs on the base pressure is almost marginal and the trends are similar to that of the ducts without ribs. The increase in the ribs height influences the behavior of the base pressure. For ducts with ribs of aspect ratio = 2/3 and 3/3, the trend is the same and is different compared to that of the duct without ribs. The base pressure decreases up to a certain value of L/D, depending on the aspect ratio of ribs. Thereafter, there is a gradual increase in the base pressure indicating rapid flow development. The increase in the base pressure results a decrease in the base drag which is needed for the design of rockets. In fact, the increase in ribs height generates more secondary vortices. These results show that the flow development is faster for the duct with ribs of RS = 3/3 compared to the other ducts with ribs. Thus, it is important to note that the condition of duct geometry (using passive controls) is of a great influence on the development of the flow field of a sudden expansion.

The effect of stagnation pressure on the base pressure is given in Fig 4 for different values of ribs height. The short height of ribs keeps the trend of the base pressure as that of the duct without ribs. The trend is changed as the ribs height is increased. For the lower value of stagnation pressure, the difference between the base pressure of the duct with and without ribs is small. For the short ducts with ribs the base pressure is much lower than that of the duct without ribs, especially for the higher values of stagnation pressure. As the duct length increases the base pressure goes above the values of the base pressure for the duct without ribs, indicating a different behavior. This variation in the base pressure with stagnation pressure for short (L/D = 2) and long (L/D = 6) ducts can be easily seen in Fig.5.

The variation of base pressure with the aspect ratio of ribs is given in Fig.6, for the long ducts. The trend is almost the same and is a function of the stagnation pressure. The difference between the values of the base pressure changes as the ribs aspect ratio is changed. Thus, it can be noted that the base pressure of sudden expansion flow is a function of a combination effect of stagnation pressure, duct length and the aspect ratio of ribs.

Figure 7 shows the distribution of wall pressure along the length of the tested ducts. For the duct without ribs, the wall pressure develops smoothly from different levels just near the base (at the recirculation zone) and converges to the atmospheric pressure at the end of the duct. This development of the pressure field is affected by stagnation pressure. The wall pressure is much lower than the atmospheric pressure for the higher values of stagnation pressure. Whereas, the trend of the pressure field is almost the same. The length of x/L required for the wall pressure to reach the atmospheric values is about 0.6, for the lower values of stagnation pressure and this length increases as the stagnation pressure is increased. The ribs introduce an oscillatory nature to the development of the pressure field. This nature is clearly seen as the ribs height is increased. This is due to the secondary vortices generated by the ribs. For the duct of RS = 1/3, the length of x/L required for the wall pressure to reach the atmospheric pressure shifts upward and is affected by the stagnation pressure. Also, this length of x/L shifts towards the base to become about 0.25 for the duct with ribs of RS = 2/3 and about 0.22 for the duct with ribs of RS = 3/3. For the higher aspect ratios, the effect of stagnation pressure on this length is marginal. This is attributed to the larger turning angle associated with the flow due to the higher aspect ratio of ribs. This result shows that the wall pressure is negative near the base and develops to be positive at a distance which depends upon the stagnation pressure and ribs height. This variation in the pressure gradient suggests that the flow fields are not simple as in the case of ducts without ribs. After the pressure becomes above the atmospheric pressure and after many oscillations the pressure field decays to reach the atmospheric pressure at the end of the duct. The early increase in the pressure may also be attributable to the action of the shock waves generated by the first rib. As the flow expands in the duct, the supersonic flow changes to a subsonic and the flow field decays as the flow propagates through the duct. In Fig. 8, the distance at which the pressure becomes above the atmospheric pressure is given as a function of ribs height (L/D = 6, $p_o/p_a = 2.69$). As seen in the figure, the pressure just near the step (at the recirculation zone) is higher, for the ducts with ribs of RS = 3/3 compared to the other case. This is due to the higher secondary vortices generated by the higher aspect ratio of ribs. Therefore, it is noticeable that the maximum number of secondary vortices is a function of the geometry of the passive controls.

Figure. 9 shows the variation of wall pressure for a short duct, L/D = 2. The pressure is negative along the duct and the flow field needs more length to complete its development. The flow field is also affected by the presence of the passive control and the development depends upon the aspect ratio of ribs. The comparison between this figure and figure 8 shows that the wall pressure near the base for the duct with ribs (RS = 3/3) is lower compared to the other ducts. This means that the secondary vortices is also a function of the duct length.

Figure 10 shows the percentage loss of total pressure as a function of L/D ratio. The pressure loss increases as the duct length is increased. This trend is the same for different stagnation pressure ratios. Whereas, the pressure loss is severe for the higher stagnation pressure. This is because, for high speed flow, as the flow regime is changed from supersonic to subsonic the pressure loss is higher. The effect of the ribs on the pressure loss depends upon the duct length. For the short ducts ($L/D \leq 3$), the pressure loss is higher than that of the duct without ribs. For the long duct ($L/D \geq 5$), the pressure loss is not much lower compared to that of the duct without ribs. This is because the flow velocity increases inside the duct more times for the long duct compared to that for the short duct. This is due to the decrease in cross section which made by the ribs. The difference between them is about 5 %. This is an excellent result which support the oscillation nature associated with the flow field.

Conclusion

High speed flow through an axisymmetric enlarged duct mounted bluff bodies (ribs as a passive control) was studied for a wide range of flow parameters. The flow field was characterized in terms of wall and base pressures measurements . The results indicate that the passive controls in the form of annular ribs are of favourable influence over the base pressure as well as the development of the flow field of an axisymmetric sudden expansion. The development is faster with the presence of such passive controls. Whereas, such bluff bodies introduce oscillatory nature to the flow field. This is due to the generation of secondary vortices inside the duct. The effect of these vortices on the total pressure loss is not high for the long ducts due to the increase in the flow velocity by the decrease in cross section due to the ribs. For the tested conditions, the ribs of aspect ratio equal to 3/1 is of excellent influence on the base pressure, keeping the trend of the base pressure is the same as that of the duct without ribs. Whereas, the higher aspect ratio of ribs increases the base pressure in which the base drag decreases.

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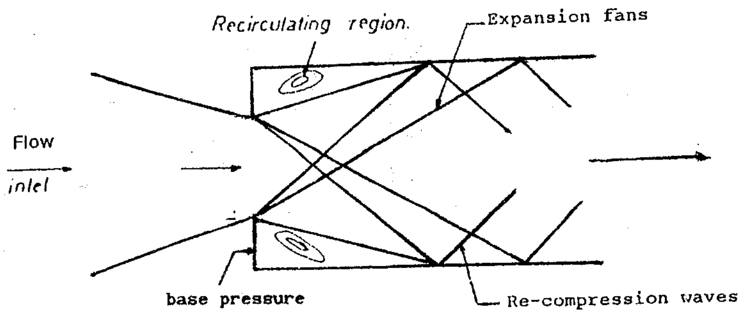
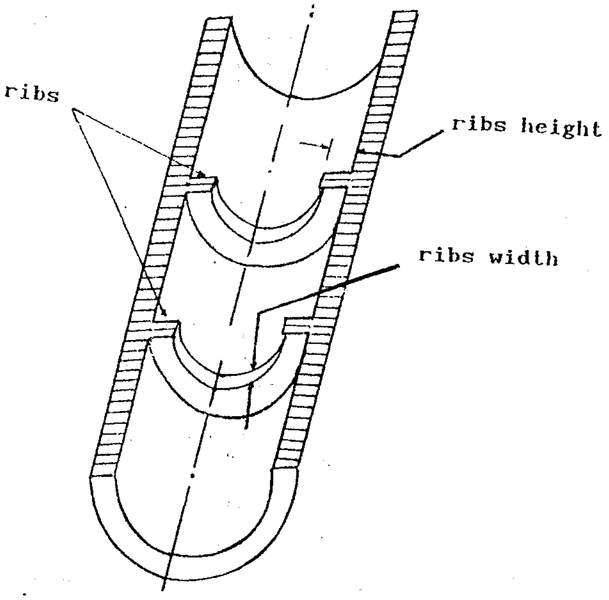


A. Flow field in a sudden expansion duct.



B. Duct model

Fig. 1

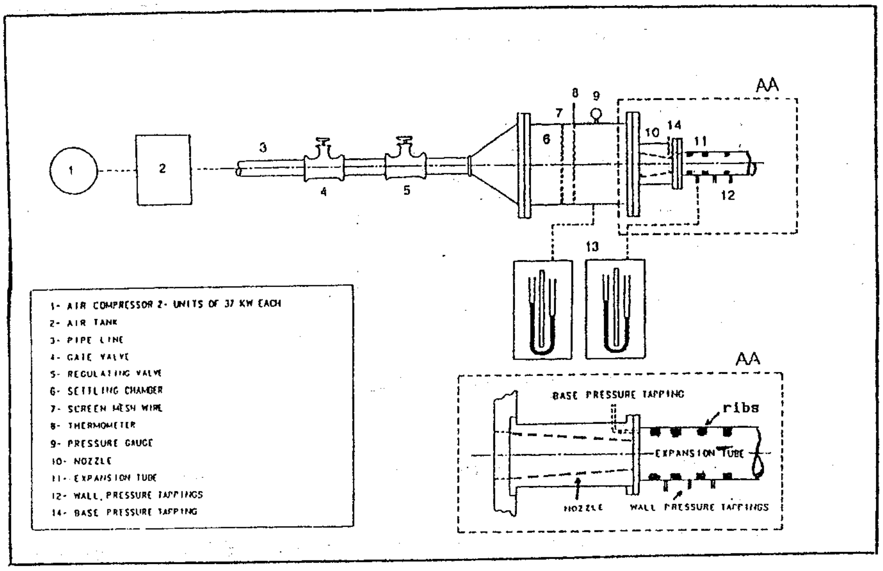


Fig. 2 Schematic of experimental apparatus

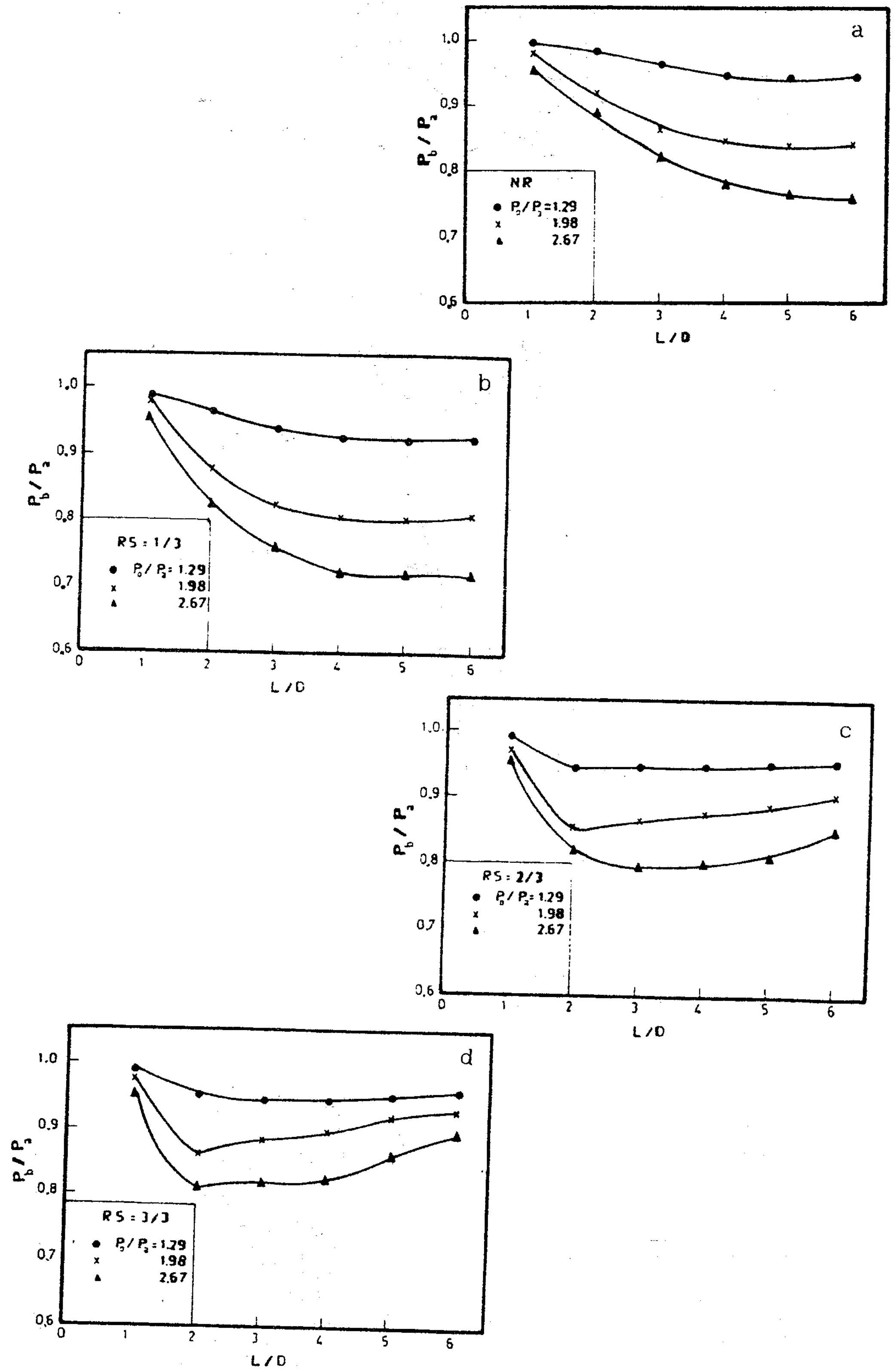


Fig.3 Variation of base pressure for different ducts

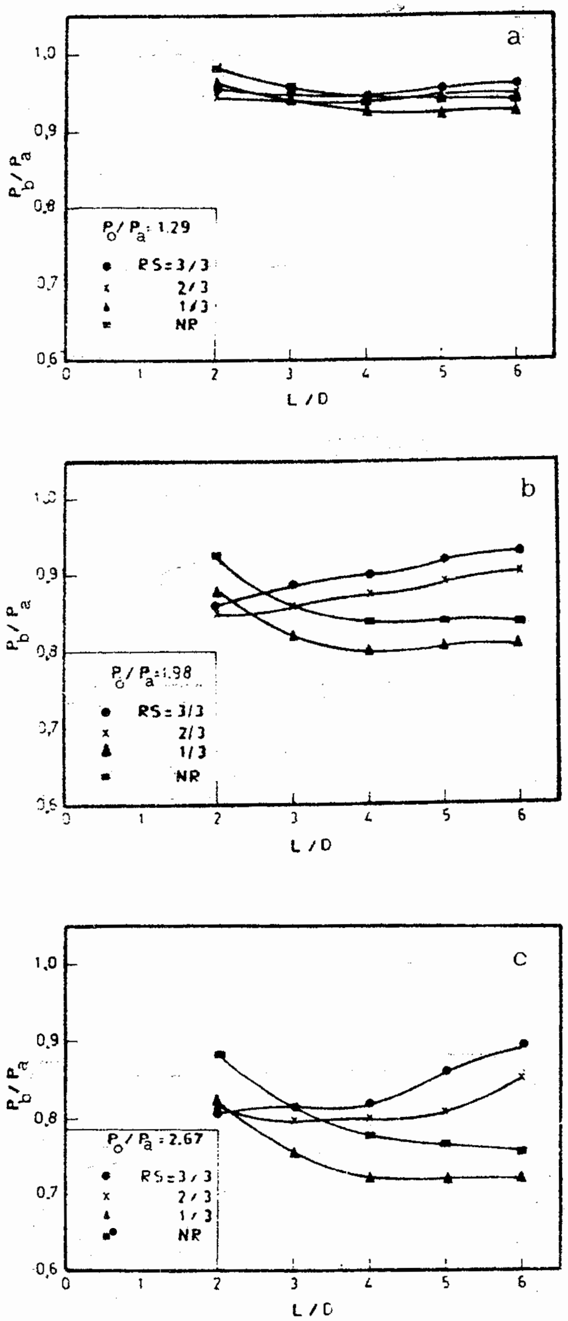


Fig.4 Effect of stagnation pressure on the base pressure

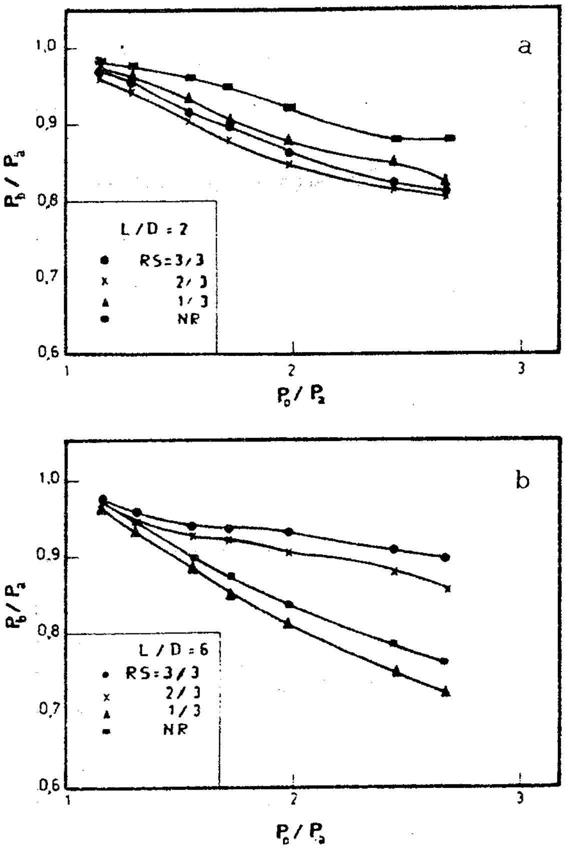


Fig.5 Variation of base pressure with p_o/p_a for short and long ducts

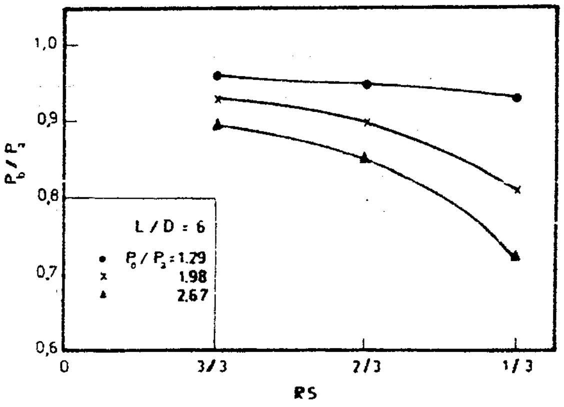


Fig.6 Variation of base pressure with RS

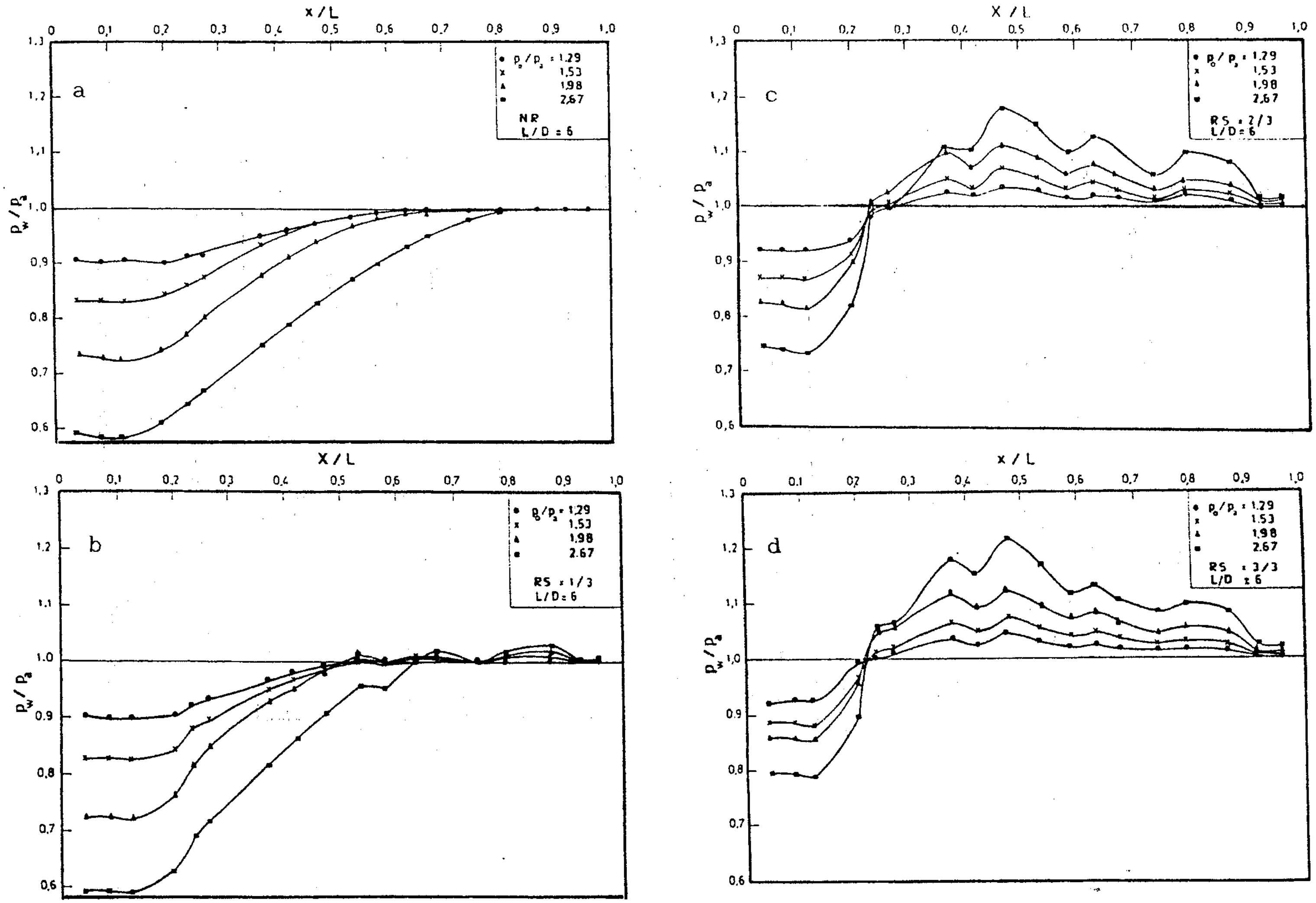


Fig.7 Distribution of wall pressure along the duct

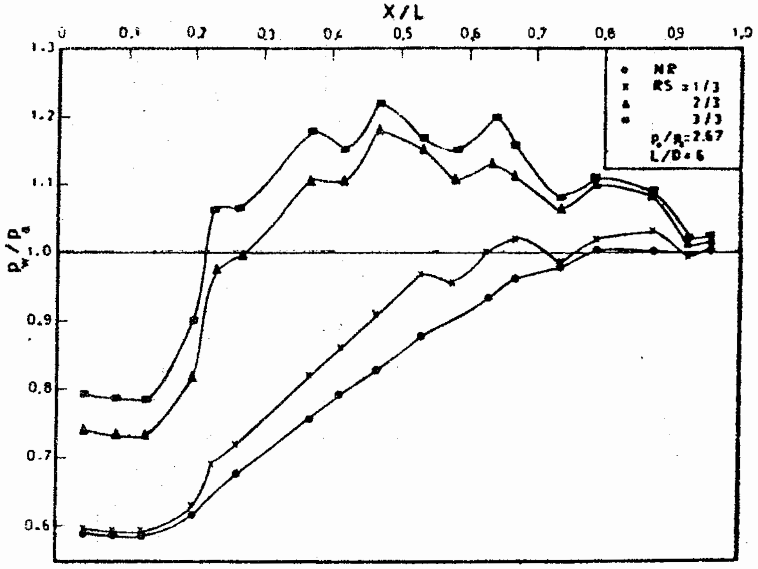


Fig.8 Distance at which the wall pressure becomes above the atmospheric

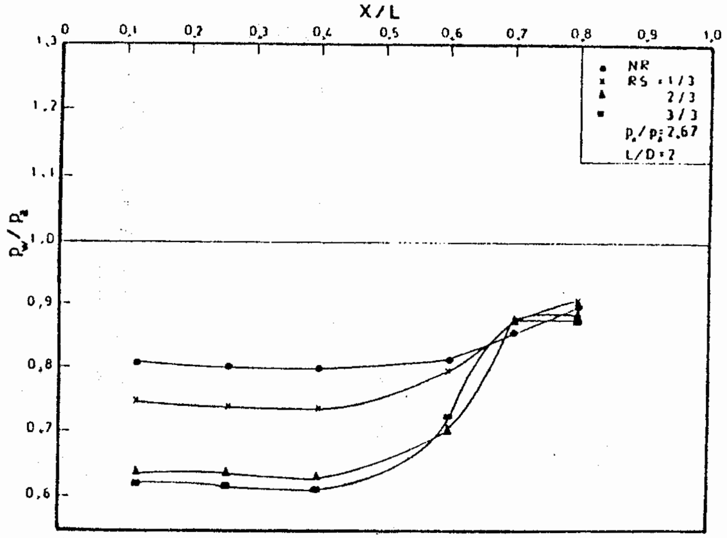


Fig.9 Variation of wall pressure for the short duct

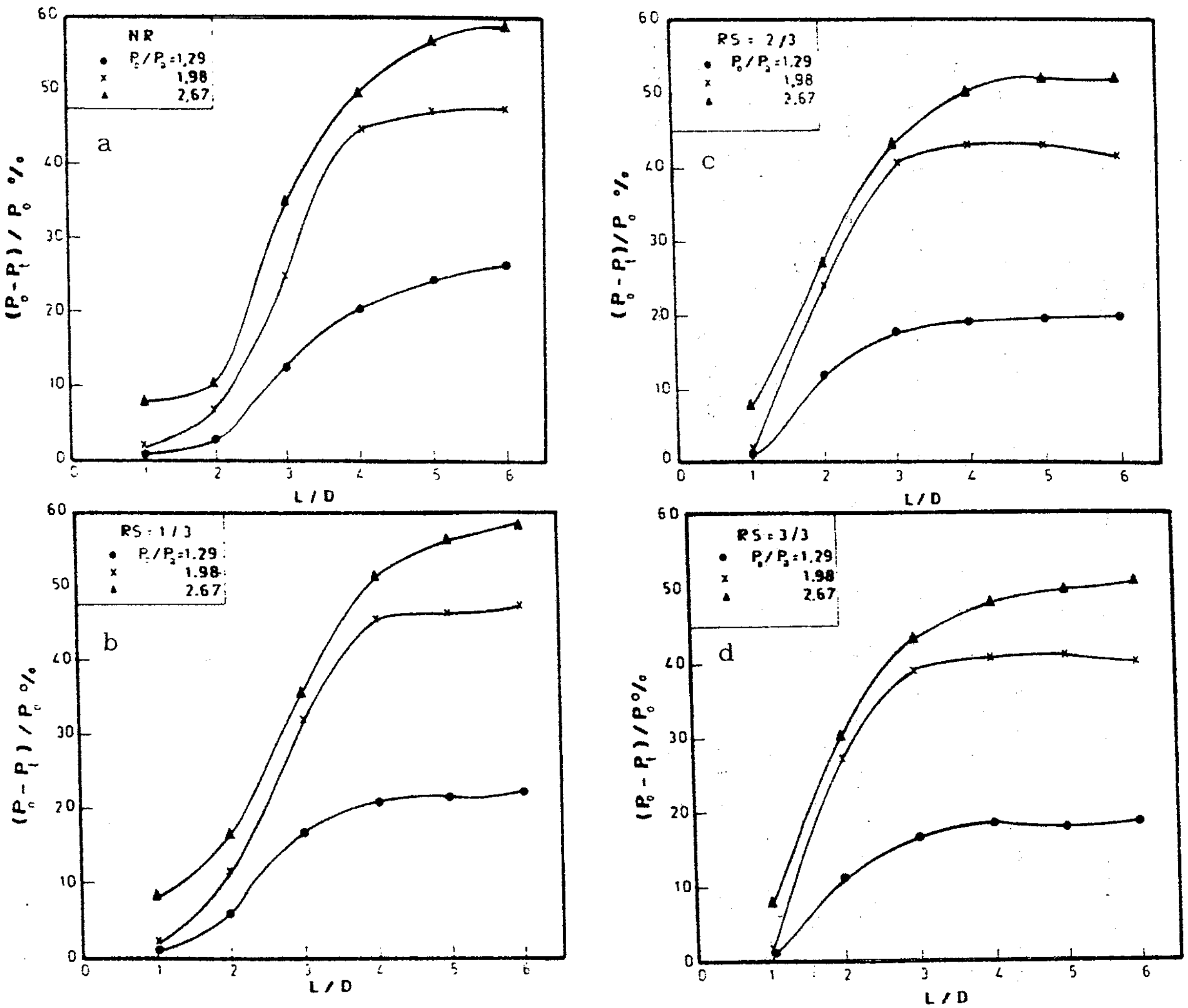


Fig.10 Effect of ribs height on the pressure loss

سريان عالى السرعة خلال اتساع مفاجئ على اجسام عارضة

يتناول البحث دراسة عملية لسريان عالى السرعة خلال اتساع مفاجئ يحتوى على اجسام عارضة حلقية موزعة على طول الانبوب المتسع وله ابعاد مستطيلة الشكل• هذه الاجسام استخدمت لتوليد دوامات ثنائية خلال الانبوب المتسع لزيادة عملية الخلط بين الموائع كما فى الصواريخ والطائرات عالية السرعة•
المائع عالى السرعة تم الحصول عليه بتمرير المائع(الهواا) خلال بوق متقارب يعمل عند ضغوط ابتدائية عالية من ١٫٢٩ — ٢٫٦٧ ضغط جوى — اوضحت التجارب ان السريان خلال الانبوب المتسع الذى يحتوى على الاجسام العارضة له نفس الخواص العامة تقريبا مثل السريان خلال الانبوب المتسع الذىلايحتوى على الاجسام العارضة مع زيادة السرعة فى تطور مجال الضغط فى الانبوب ذات الاجسام العارضة•

كذلك وجد ان تاثير هذه الاجسام وما يصاحبها من دوامات عند القاعدة كبير بالذات فى الانبوب ذات الطول عنه فى الانبوب القصير واعطى زيادة فى الضغط عند القاعدة مما قلل من المقاومة المصحوبة للضغط عند اللقاعدة والذى لها اثرها الفعال عندالتصميم للصواريخ والطائرات ذات السرعات العالية وكان التاثير مرتبط بالضغط عند الدخول بالنسبة للبوق وابعاد الاجسام العارضة داخل الانبوب المتسع وكذلك طول هذا الانبوب•