THERMAL EFFECTS OF TUBES DRIVEN BY SUPERSONIC JETS

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Abstract

Supersonic air jets impinging upon a cavity (H-S tube) have been studied to explain the resulting heating phenomenon. Axisymmetric convergent nozzle and convergent divergent nozzle (M = 1.3) were used to produce under and over expanded supersonic jets. Such jets were used to drive the tube which was placed co-axially with the nozzle. One end of the tube was open facing the jet and the other end was closed. The tested models were a tube with smooth surfaces and in the second type, annular grooves of rectangular cross section were made on the inner surface of the tube. Measurements of the total pressure and total temperature at the closed end of the tube were made for different values of nozzle to tube spacing. The results show that flow oscillations are achieved within the tube for both overexpanded and underexpanded jets. The grooves increase the flow oscillation, resulting a higher rise in the total temperature at the closed end.

Notation

p_a : ambient pressure
p_e : nozzle exit pressure
p_o : stagnation pressure
T_n : temperature outside the nozzle
T_o : stagnation temperature
T_t : Total temperature
θ : The isentropic temperature difference = $(T_t - T_n)/(T_o - T_n)$

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MANUSCRIPT RECEVED FROM DR: Gamal H. Moustafa, AT: 26/3/1997,
ACCEPTED AT: 24/5/ 1997, PP. 49-63,
ENGINEERING RESEARCH BULLETIN, VOL. 20, NO. 2, 1997,
MENOUFIYA UNIVERSITY, FACULTY OF ENGINEERING,
SHEBIN EL-KOM, EGYPT. ISSN. 1110-1180.

Introduction

When a jet from a moderately underexpanded nozzle ($0.48 \le p_a/p_o \le 0.26$, $1.1 \le p_e/p_a \le 2$) is made to impinge on a cavity (for example, a tube with its end facing the jet opened and the other end closed, Fig.1), intense sound waves of high frequency oscillations are generated at certain axial spacings between the nozzle and the open end of the cavity. Such an arrangement is called a resonance tube or Hartmann oscillator (Hartmann, 1931) and it is of considerable practical importance (Iwamoto,1974). It is used as an H_2-O_2 Rocket engine Igniter, a Resonance tube Transformer and as a Sonic atomizer that can mix efficiently petroleum based fuels and air to improve combustion in industrial and residential oil burners, and gas turbines, internal combustion, and steam engines. The flow phenomenon can be explained as follows : When a jet is made to issue from a nozzle, it accelerates to supersonic speed directly after emerging from the nozzle. It then returns to subsonic speed through a compression shock wave. The result is a series of stationary conical shock waves along the jet axis. When a tube or cavity is placed near one of shock locations, self sustaining oscillations are set up by resonant waves within the tube. These resonant shock waves travel up the jet to reflect at the nozzle exit. The resultant shifting of the conical shock waves within the jet *produces a high intensity sound. The use of Schlieren photographs* by Hartmann (1931) shows that the main flow periodically charges and discharges the tube.

In 1954, Sprenger conducted experiments similar to those of Hartmann using long cavities (long tubes) and discovered the thermal properties of the flow field. Such an arrangement of the nozzle and long tube constitutes what is known as a Hartmann-Sprenger tube (H-S tube). Przirembel and Fletcher (1977) found that the end wall temperature increases with the length / diameter ratio of the tube. Earlier, Sprenger (1954) found that the maximum temperature obtained with the resonance tube can be reached at a tube length to diameter ratio of 34. Such a high temperature is capable of damaging valves of high pressure vessels, with the same arrangement of H-S tube. In fact, Sibulkin and Vrebalovich, (1958) *found that the thermal effect is due to* irreversible heating by shock waves and wall friction. Also, Sprenger (1954) and Brocher et al, (1970) proved that it was even possible to generate flow oscillations with a subsonic jet.

Numerous studies have been devoted to H-S tubes driven by supersonic underexpanded jets and subsonic jets to investigate the oscillation mechanism as well as the acoustic and thermal properties of the devices. Also, most of these investigations were done on jets driven smooth tubes. However, no work seems to have been done on the resonance tube driven by supersonic overexpanded jets. Hence, in the present study, the main objective is to experimentally study the flow field in a tube driven by supersonic jets, for a wide range of nozzle to tube spacing and to investigate the effect of the inner surface conditions on the flow field. Tubes with straight inner surface (smooth tube) and others with inside surface grooves were tested, with different values of tube length. A comparison between the flow field within the tube when driven by over and under expanded jets is highlighted.

Theory of Flow Development

Using flow visualization, Iwamoto (1986) described the flow field within a tube driven by supersonic jets (Fig.2) as follows: During the inflow process, the pressure downstream of the Mach disc (Fig.2a) is almost atmospheric. The oblique shock wave which extends towards the axis of the tube appears at the lip of the tube since the air speed remains supersonic across the reflected oblique shock wave in the jet. Outside the tube, the pressure is relatively high near the lip and it becomes atmospheric downstream as the air passes through a wave system comprising the expansion waves and shock waves along the wall of the tube. Immediately after the tube disgorging starts (Fig.2b), the shock which comes back from the closed end merges with the stationary oblique shock at the open end and moves upstream in the nozzle jet. At the merging point of two shocks, the contact surface and the expansion wave originate. At the same time, another expansion wave occurs at the lip of the tube due to the diffraction of shock wave. One part of the expansion wave weakens the shock wave and moves upstream in the jet and the other part goes into the tube. The shock wave which moves upstream in the jet merges with the Mach disc, and the contact surface and the expansion wave are generated at the merging point. Thereafter, this shock wave, being continuously weakened by the arriving expansion waves from the lip of the tube becomes stationary after moving slightly upstream. At this time the fluid particle right behind the shock wave moves towards the open end to be choked and a quasi steady outflow is established. In Fig.2c, the expansion wave in the tube moves towards the closed end where it is then reflected. When this reflected expansion wave reaches the open end, the compression wave is reflected there and moves towards the closed end. A part of this expansion wave lowers the Mach number of the outflowing jet from the tube and as a result the shock in the tube jet is strengthned and pulled towards the open end. Thereafter, the expansion wave reaches the shock in the nozzle jet and weakens it, and is also pulled towards the open end. Since expansion waves come out of the tube continuously, the pre-described process taken place gradually and finally a quasi steady inflow is established. Finally, the flow is relatively stable and one can conclude that the flow pattern (of the inflow into the tube) is very similar to that of a steady flow through a tube opened at both ends.

Experimental Apparatus and Procedure

The experimental apparatus is shown schematically in Figure 3. Compressed dry air from a storage tank was passed through the control valves and restored to a stagnation state in the settling chamber, before being accelerated to a prescribed velocity value through the nozzle. The air jet from the nozzle was used to drive the tube. A circular convergent nozzle and a convergent - divergent axisymmetric nozzle were designed. At first, the tube was driven by underexpanded jets issuing from the convergent nozzle and then it was driven by overexpanded jets issuing from the convergent divergent nozzle. The exit diameter of the nozzles (d) was 10 mm. The design Mach number of the supersonic nozzle (M) was 1.3. Two circular tube models (a smooth one and another with annular surface grooves) were tested. The inside diameter (D_i) of the tested tubes was 10 mm. The outer diameters (D_o) of the tubes were 11 mm and 20 mm for the smooth tube and that with surface grooves, respectively. The tube length (L) was varied from 120 to 400 mm. Annular grooves of two dimensional cross section (2mm x 2 mm) were made on the inner surface of the tube. The first groove was made at a distance of 10 mm from the opening end and the second one was at 10 mm from the first and then at an interval of 20 mm, Fig. 1.

Measurements of total pressure and total temperature at the closed end of the tube were made for different values of nozzle tube spacing (s/d). The total pressure (p_t) was measured by a total pressure probe of 0.6 mm inner diameter, fixed to the closed end at the tube axis. The total temperature was measured by a copper-constantan thermocouple soldered to the closed end. The thermocouple was connected to a millivoltmeter. The wall static pressure reading (p_w) was taken from taps distributed along the tube wall (smooth tube). The stagnation pressure was fixed during the experiments to be equal to 2.7 atmospheres. The room temperature was uniform at 26 ± 1 C° and, the stagnation temperature in the settling chamber was uniform at 35 ± 1 C°. The measured values of the total and static pressures were repeatable within ± 3%.

Results and Discussion

The distribution of wall static pressure measured along the smooth tube is shown in Fig.4. The wall pressure experiences a slight increase when the tube was driven by the underexpanded jet. Whereas, the wall pressure decreases on moving towards the closed end when the tube was driven by the overexpanded jet. This is because, for the case of underexpanded jets, the expansion waves at the nozzle exit reflect from the tube lip to enter the tube as a compression waves. This leads to an increase in the static pressure. For the case of overexpanded jets, an opposite periodic process exists, Brocher et al (1970).

Figure 5 shows the variation of total pressure measured at the closed end of the smooth tube when driven by under and overexpanded jets. Since the tube was placed co-axially with the nozzle this variation in the total pressure is equivalent to the decay of free jets. It is clear from the figure that the flow pattern within the tube is very similar to that of a steady free jet flow (Krothapalli et al, 1990). For instance, in the region close to the nozzle exit, the shock wave (Mach disc) exists and is so strong (indicated as a cusp in the total pressure variation). This region is equivalent to the potential core region in the case of free jets (Krothapalli et al, 1990). The cusp (the position of the shock wave) is found at s/d = 0.4 when the tube was driven by the underexpanded jet whereas, it results at s/d = 1 for the case of the overexpanded jet. The decay of the underexpanded jet is slower than that of the overexpanded jet. This is because the strength (shown by the pressure drop) of the shock wave associated with the overexpanded jet (M = 1.3) is higher than that associated with the underexpanded jet (M = 1). It is important to note that, in a supersonic flow with a single shock wave ahead of the pitot tube, a large pitot pressure corresponds to the low Mach number and vice versa. The figure shows that , in the case of the overexpanded jet, the supersonic flow changes to subsonic flow directly near the nozzle exit and is faster than that for the case of the underexpanded jet. This makes the decay of the overexpanded jet to be faster than that of the underexpanded jet, (Krothapalli et al, 1990). This behavior of total pressure is similar and is independent of the tube length. It should be noted that the decay of total pressure is the same for the free jet as well as for the jet issuing into a tube placed co-axially with it.

The decay of total pressure for tested tubes driven by underexpanded jets is given in Fig.6. The effect of the tube length is insignificant, especially for the large spacing between the nozzle and tube. Also, the surface grooves have a little effect on the pressure field as the spacing is increased. The oscillation pattern in the near field is slightly higher for the tube with surface grooves. This is because the surface grooves generate more expansion and compression waves which propagate through the tube resulting more flow oscillations. In the far region, the pressure field is the same for both tested tubes. The result in the far region, is in good agreement with the behavior of low incompressible free jets, (Krothapalli et al, 1990).

Figure 7 shows the decay of total pressure for tested tubes driven by overexpanded jets. The oscillation pattern associated with the flow field for small values of the nozzle tube spacing depicts the shock wave which travels into the tube. The strength and position of these shock waves are changed with the tube length, especially for the case of tube with surface grooves.

Also, the decay of total pressure is faster for the long tube with surface grooves compared to the short tubes and to that driven by the underexpanded jet, Fig.6. This is because the number of surface grooves increases with the tube length. Thus, the expansion waves as well as the shock waves become more stronger. Due to this fact the change to subsonic flow becomes faster and the decay of the pressure field is considerably accelerated. For the large spacing between the nozzle and the open end of the tube, the decay of the total pressure is similar for all cases.

Figure 8 indicates the thermal phenomenon associated with the flow field for the jet driven smooth tubes. The ordinate in this figure is the ratio of the temperature rise at the closed end of the tube to the difference between the stagnation temperature and the temperature outside the nozzle (the isentropic difference), denoted by θ. The results show that the temperature rise at the closed end of the tube is affected by the flow regime (either over or under expanded flows) and tube length. The rise in the total temperature is higher when the tube was driven by overexpanded jets as compared with that when the tube was driven by underexpanded jets. This is because the fluid within the tube is excited to a violent oscillation when the tube was driven by the overexpanded jet, as previously shown in Figures 5, 6 and 7. The maximum increase in the total temperature is obtained when the tube was placed at a distance from the nozzle (s/d) equals 0.2, for the tube driven by the overexpanded jet. This location is shifted to a distance equals 8.5, for the case of the tube driven by the underexpanded jet. After the maximum rise is reached the temperature rise decreases as the distance between the nozzle and the open end is increased.

The variation of total temperature with nozzle tube spacing for tubes driven by the underexpanded jet is given in Fig.9. The results show that the tube length affects the rising in the total temperature. Also, the position of maximum temperature is changed as the condition of the tube surface is changed. The maximum temperature is at s/d = 8.5 for smooth tube whereas, it is seen at s/d = 4.2 for the tube with surface grooves. The results for the same tubes when driven by the overexpanded jet is shown in Fig.10. The position of the maximum temperature rise for the tube with grooves is shifted to be at s/d = 0.5. This indicates that the thermal phenomenon is also a function of the surface conditions as well as the flow regime. The maximum temperature is about 1.6 times the free stream temperature (temperature outside the nozzle), for tubes with surface grooves driven by the overexpanded jet (L/d = 1.6, nozzle to tube spacing = 0.5).

Conclusions

A series of experiments on a jet driven-tube has been performed to study the oscillating behavior of the flow field and accompanying thermal phenomenon. Supersonic over/ underexpanded jets were used to drive the tube. Measurements of total pressure and total temperature were made at the closed end of the tube. The driven tube was firstly made smooth and then annular grooves of rectangular cross section were made along the inner surface of the tube. Results of these experiments show that the oscillation and the associated thermal phenomenon are directly related to the size (strength) of the shock wave cells. The flow behaviour is affected by the tube length as well as the condition of the inner surface of the tube. The nozzle tube spacing also affects the development of the flow field as well as the thermal phenomenon. Finally, the flow regime has a significant effect on the thermal process. The behaviour of the flow field within the tube is almost similar to that of a steady free jet.

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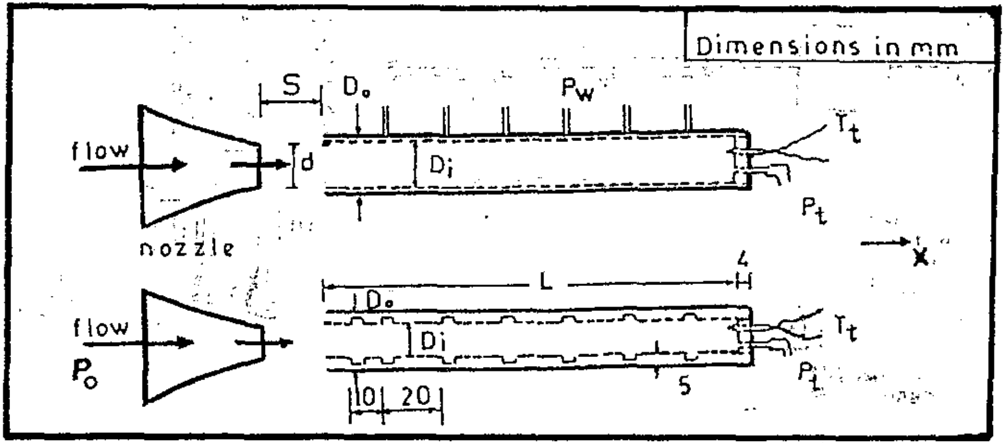
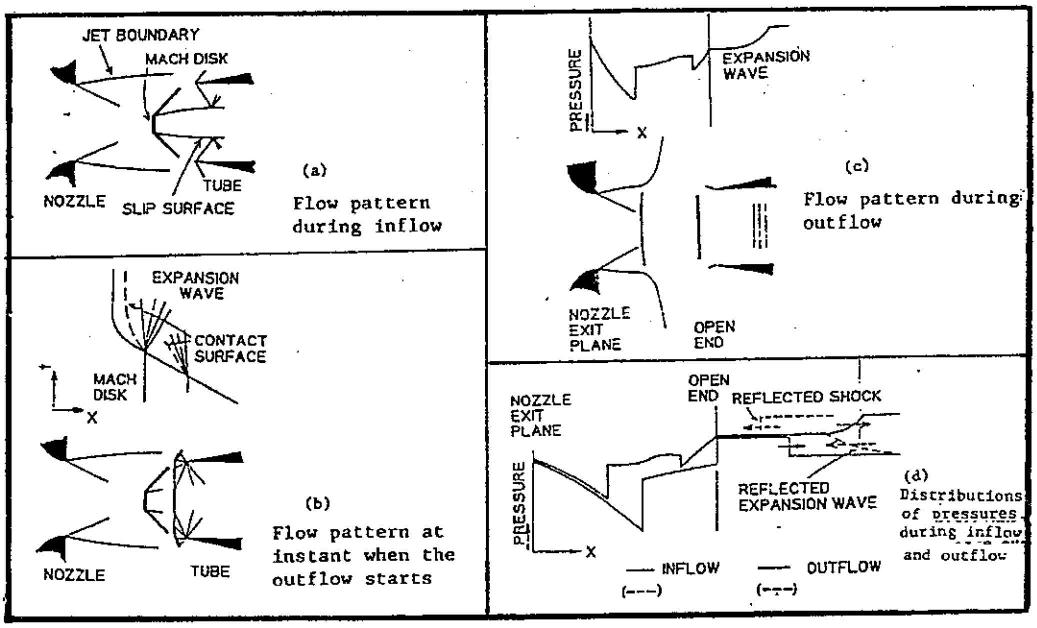


Fig.1 Jet Impinging on a tube



(a) Flow pattern during inflow

(b) Flow pattern at instant when the outflow starts

(c) Flow pattern during outflow

(d) Distributions of pressures during inflow and outflow

Fig.2 Flow development

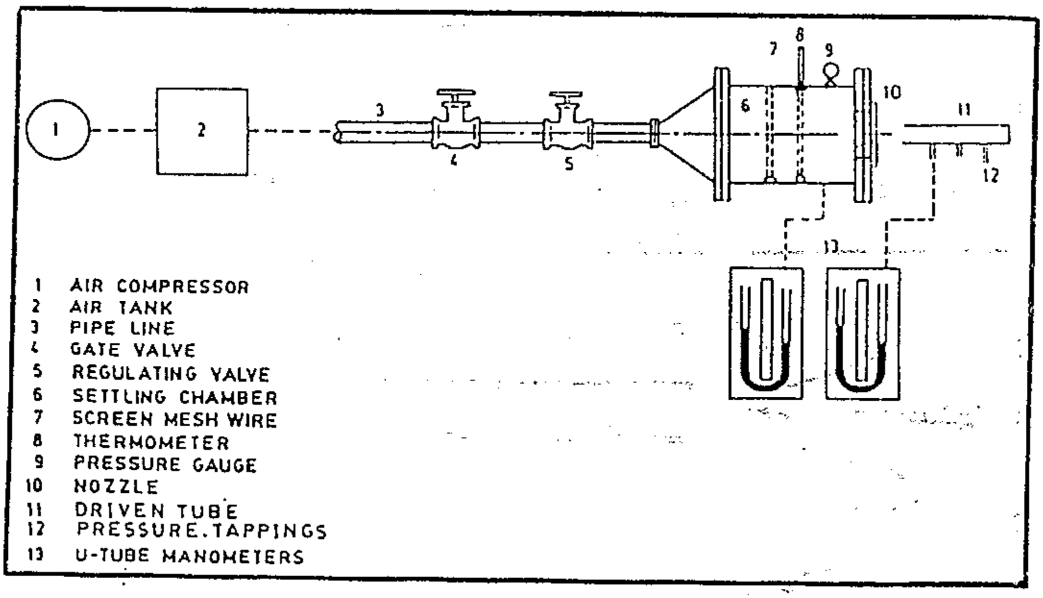


Fig. 3 Schematic of experimental apparatus and test section.

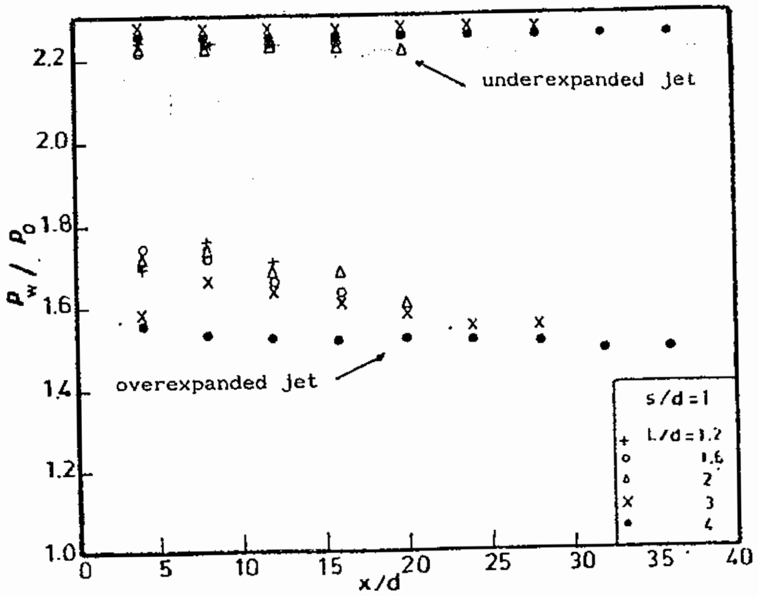


Fig. 4 Variation of static wall pressure with nozzle tube spacing.

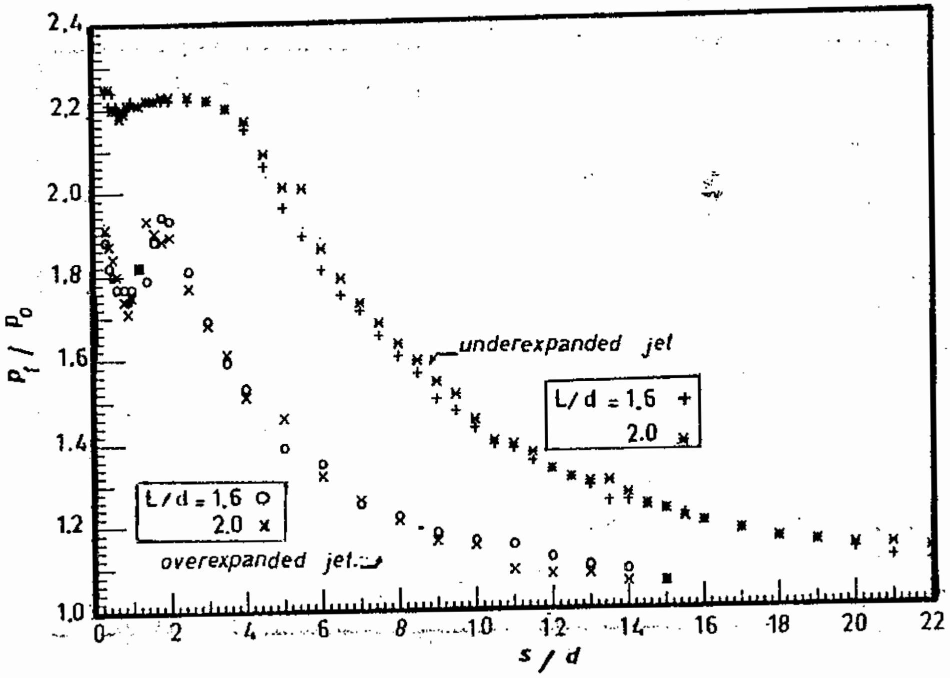


Fig. 5 Decay of total pressure for smooth tube.

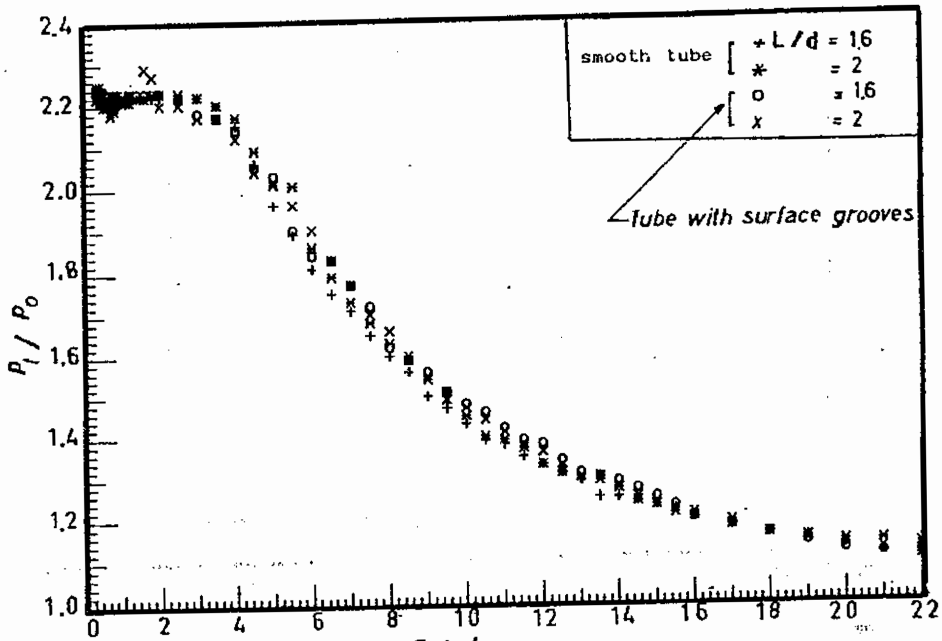


Fig.6 Decay of total pressure for tested tubes driven by underexpanded jets.

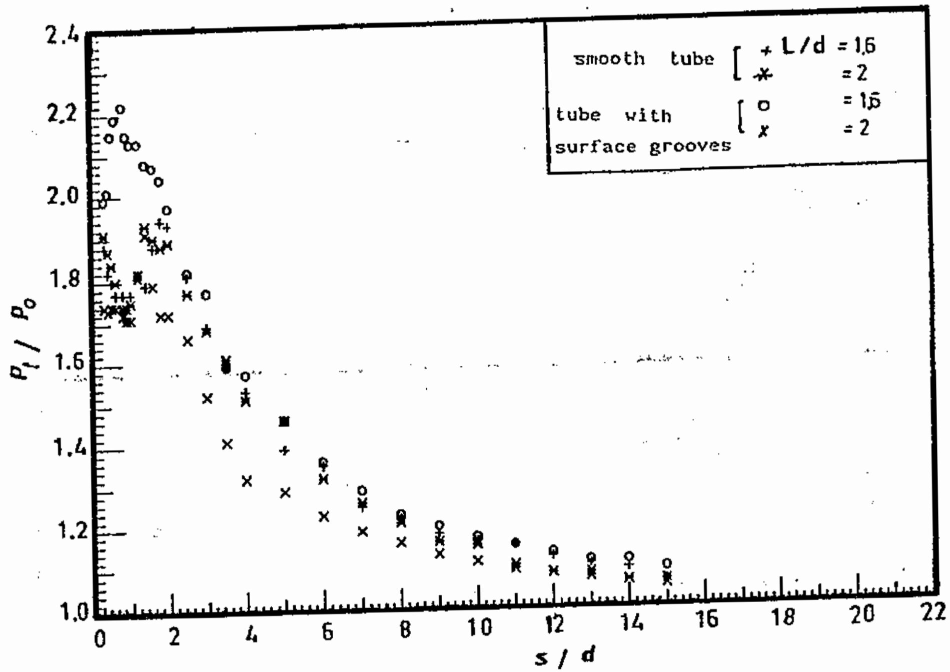


Fig.7 Decay of total pressure for tested tubes driven by overexpanded jets.

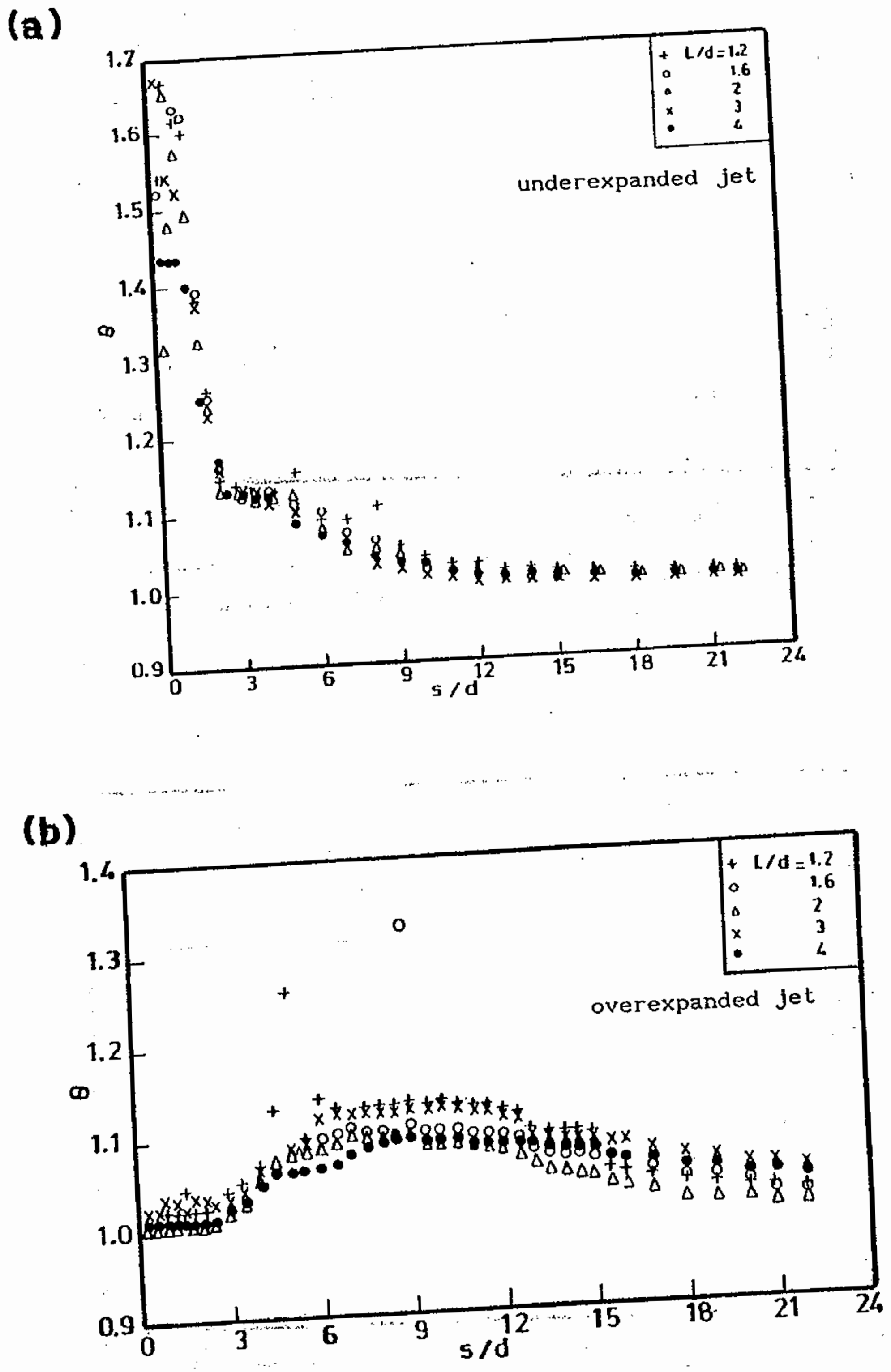


Fig.8 Variation of total temperature for smooth tubes.

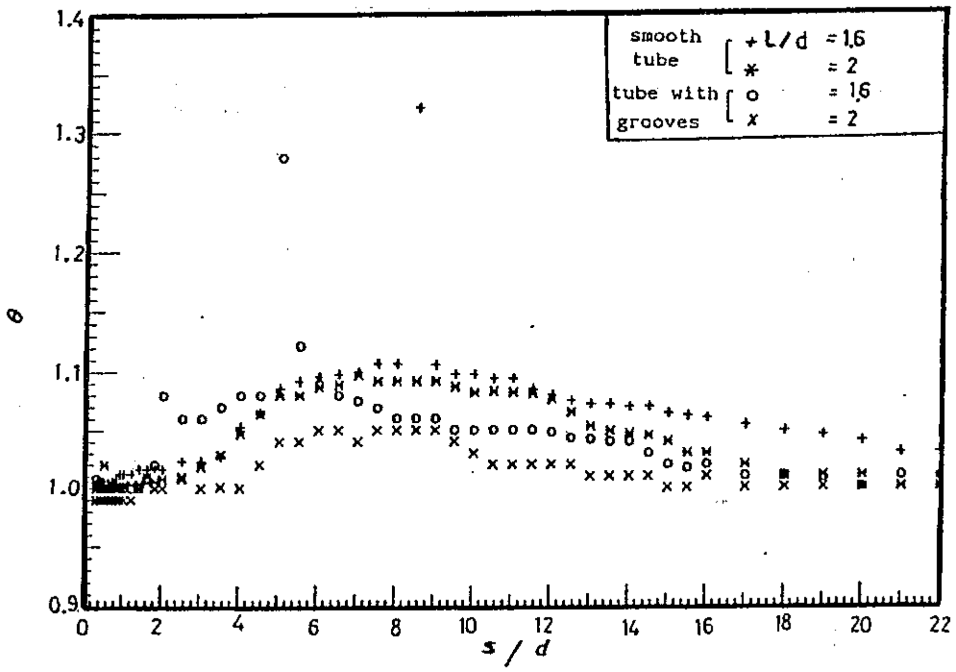


Fig.9. Variation of total temperature for tested tubes driven by underexpanded jets.

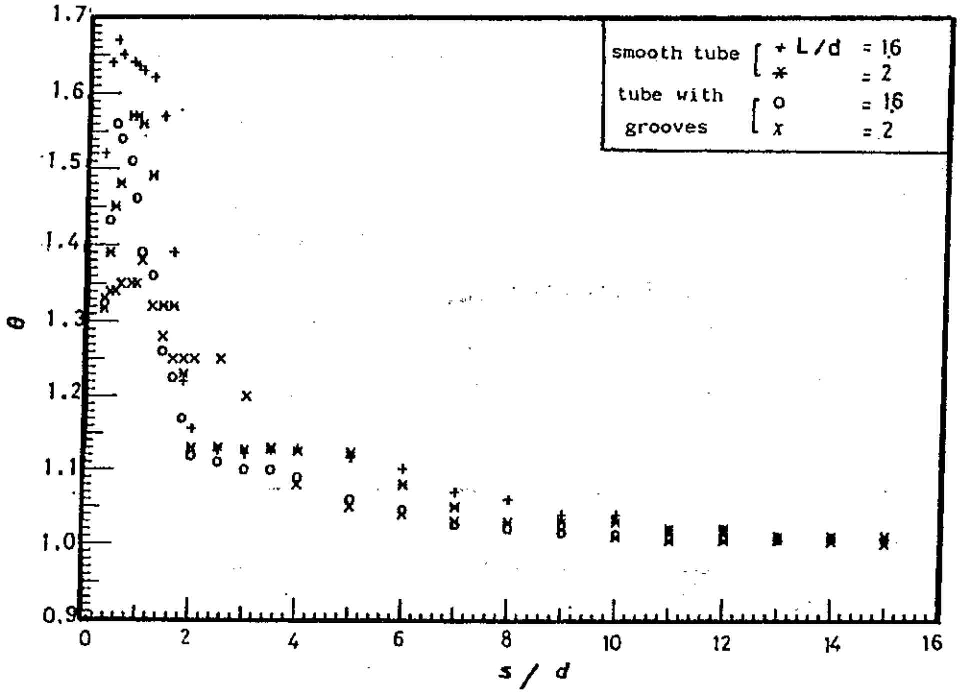


Fig.10 Variation of total temperature for tested tubes driven by overexpanded jets.

التأثير الحرارى لأنبوب هارتمان سبرنجر

د. جمال حافظ أحمد مصطفى

يعتبر دراسة إصطدام النفث ذات السرعات الأعلى من سرعة الصوت بأنبوب مفتوح طرفه المقابل للنفث بينما طرفه الخلفى مغلق وهو ما يعرف بإسم إنبوب هارتمان سبرنجر ذات أهمية خاصة حيث يستخدم فى كثير من التطبيقات الهندسية الحديثة مثل عملية بدء الشرارة فى الصواريخ الحامله للمركبات الفضائية وتطبيقات أخرى عديده مبينه بالبحث.

فى هذا البحث إستخدام نوعان من الأبواق لزيادة سرعة النفث. النوع الأول منها وهو بوق متقارب وتم عمل التجارب عندما يعمل هذا البوق فى ظروف ليعطى نفث ذات سرعات أعلى من سرعة الصوت أو ظروف تحت التمدد والبوق الأخرى هو من النوع المتقارب المتباعد تم تصميمة ليعطى نفث ذات سرعات عالية حيث صمم البوق ليعطى رقم الماخ له =١,٣ وتم عمل التجارب تحت ظروف ليعطى نفث له نسبه ضغط عند المخرج إلى تلك عند المدخل أعلى بقليل من النسبه المصاحبه لتلك المصمم عليها البوق أو ما يعرف بفوق التمدد. وإستخدام نوعان من الأنابيب. النوع الأول وهو إنبوب ذات أسطح مستوية من الداخل أو ما يعرف بالأنبوب ذات الأسطح الملساء والأخر تم عمل جروف فى السطح الداخلى للأنبوب على أبعاد موضحة بالبحث. وتم قياس الضغط ودرجة الحرارة عند الطرف المغلق للأنبوب وكذلك قياس الضغط على إمتداد طول الأنبوب. وتبين من التجارب إرتفاع درجة حرارة السطح عند الطرف المغلق بنسبه عالية وكانت نسبه الزيادة فى درجة الحرارة معتمده على نوع النفث المستخدم اما فوق أو تحت التمدد وكذلك كان لطبيعة السطح الداخلى للأنبوب أثر بالغ فى إرتفاع درجة الحرارة حيث تبين أن الجروف الداخلية أدت إلى أرتفاع درجة الحرارة بنسبة أعلى من تلك التى ظهرت عند إستخدام الأنبوب ذات الأسطح الملساء وإرجع البحث إرتفاع درجة الحرارة إلى موجات التمدد والإنضغاط المصاحبه للنفث والتى كان للجروف أثر كبير على طبيعة هذه الموجات.