A STUDY OF SUPERSONIC WET STEAM FLOW INCLUDING SHOCK WAVES THROUGH CONSTANT AREA DUCTS
PART (I): EXPERIMENTAL STUDY

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ABSTRACT

The first part of this paper is concerned with investigating, experimentally, the structure of shock waves involved within the supersonic flow of wet steam through a constant area duct or pipe. The present experimental program comprises measurements of the variation of wall pressure along the tested duct. The measured pressure distributions along the tested ducts or pipes and under different boundary conditions are directed to obtain the characteristics of interaction between the shock wave and the boundary layer. This program is carried out at different boundary conditions such as initial and back pressure values, initial quality of supplied steam and duct geometry (or length). The obtained results declare that these boundary conditions affect significantly both the shock structure and the interaction characteristics.

Keywords: Wet steam, Supersonic flow, Shock wave-boundary layer interaction, Constant area duct, Pressure recovery.

INTRODUCTION

When a normal shock wave is generated inside a duct through adjusting the back pressure, generally the produced shock can interact in several configurations with the boundary layer on the duct wall. This interaction can be responsible for a large loss in pipe delivery pressure [1-2], aero-thermodynamic loss in transonic-supersonic compressor cascades [3] and transonic steam turbine cascades [4] and flow separation in diffusers [5]; on flat plate [6-8] and upon a curved wall [9]. For example, Seddon [6] demonstrated the nature of separation and reattachment of turbulent boundary layer on a flat plate due to its interaction with a strong normal shock. He reported that the separation occurs at a point two boundary layer thickness downstream of the start of interaction whilst the reattachment lies at 12 thickness. Doerffer [9] studied experimentally the interaction characteristics between normal shock wave and turbulent boundary layer upon a convex wall. He concluded that increasing the wall curvature causes to decrease the separation length. Shapiro [10] has clearly concluded that there is often a back flow in the boundary layer near the shock. This back flow produces a seperation of the flow from the duct or pipe wall. He also accounted to that as the flow separates from the duct wall then passes through a system of accelerations and shocks. Thus, when the flow reaches subsonic velocities; it diverges and fills the duct again.

The primary objective of any experimental program is to share in formulating simple models or semi-empirical correlations and to check the assumptions and results of such a theory. The earlier experimental studies of shock wave-boundary layer interaction have been conducted in conventional continuous tunnels, shock tunnels, gun tunnels and Ludwieg tubes [7]. In order to make a meaningful study of the characteritics of this interaction, measurements of one or more than one of skin friction; heat transfer and wall and flow field pressure are required. Measurements of wall pressure distribution have been shown by Waltrup and Billig [11],

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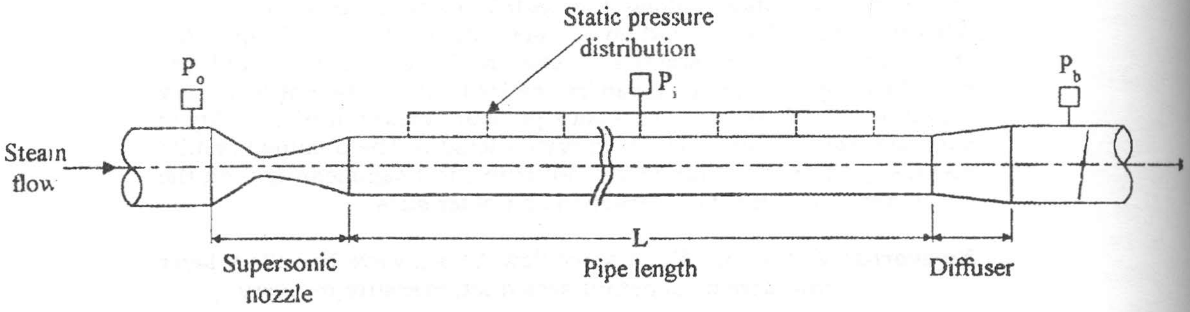
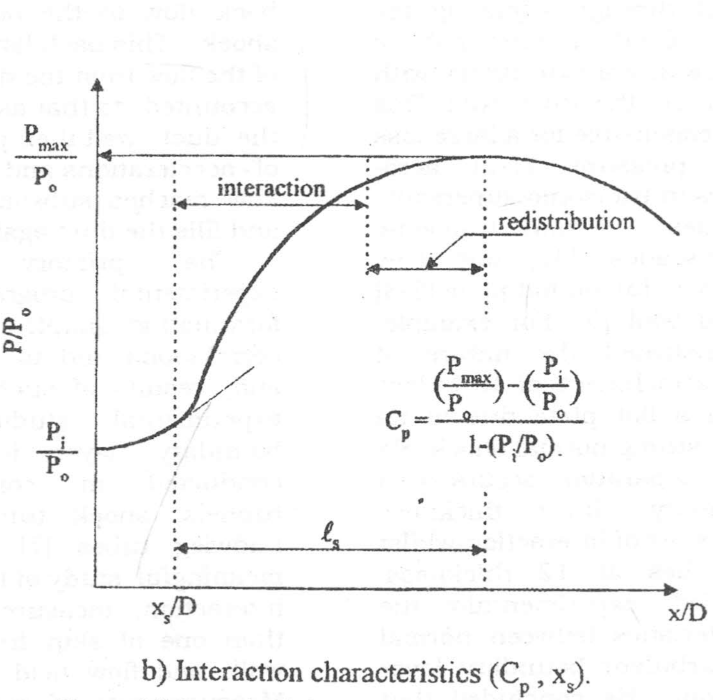
Petr [12], Livesey; *et al.* [5] and Kamal; *et al.* [13] to be an extremely good indicator of shock wave-boundary layer interaction in ducts, nozzles and similar devices. Furthermore, Grag and Settles [14] used Miniature pressure transducers to establish a database on the fluctuating pressure loads produced on aerodynamic surfaces beneath shock wave-boundary interactions.

A typical wall pressure distribution along a pipe is fed by a supersonic flow from a convergent - divergent nozzle as illustrated and discussed previously by Livesey and Others [5] has been shown in Figure 1. This figure describes and presents the characteristics of interaction between shock wave and boundary layer. These characteristics include beside the wall pressure distribution both the shock position (x_s) and length of the interaction region or the shock length (ℓ_s). Interaction characteristics have been reported for gas flow through diffusers [5] and nozzle fed ducts [13, 15, 16].



a) Definitions.



b) Interaction characteristics (C_p , x_s).

Figure 1 Schematic of shock wave-boundary layer interaction .

The interaction of a shock wave with a boundary layer has been the subject of many researches because of practical value as well as interest of the problem as a physical phenomenon. However, knowledge about the problem of shock wave-boundary layer interaction in two phase flow lags behind knowledge about this problem in the case of single phase flow. This is due the complexity of simulating the two-phase flow beside the difficulty of performing experimental measurements in these flows. Only one attempt has been devoted by Ibrahim [17] to analyze the problem experimentally in a two-phase gas-solid mixture flow through cylindrical ducts.

The goal of the current study is to assess experimentally the shock wave structure beside the characteristics of shock wave-boundary layer interaction for steam flow through constant area ducts or pipes. In the present experiments, measurements of wall pressure distributions along the tested pipes are made to obtain the interaction characteristics. Effect of some boundary conditions such as; back pressure, inlet pressure, initial steam quality and pipe length on the pressure distribution and consequantly interaction characteristics are considered also in the currenet study.

APPRATUS AND MEASUREMENTS

Figure 2-a shows a general layout for the experimental set up that has been used in the present work. The set up consists mainly of a fire-tube boiler, a heat exchanger, a test section, a surface condenser and some measuring and control devices.

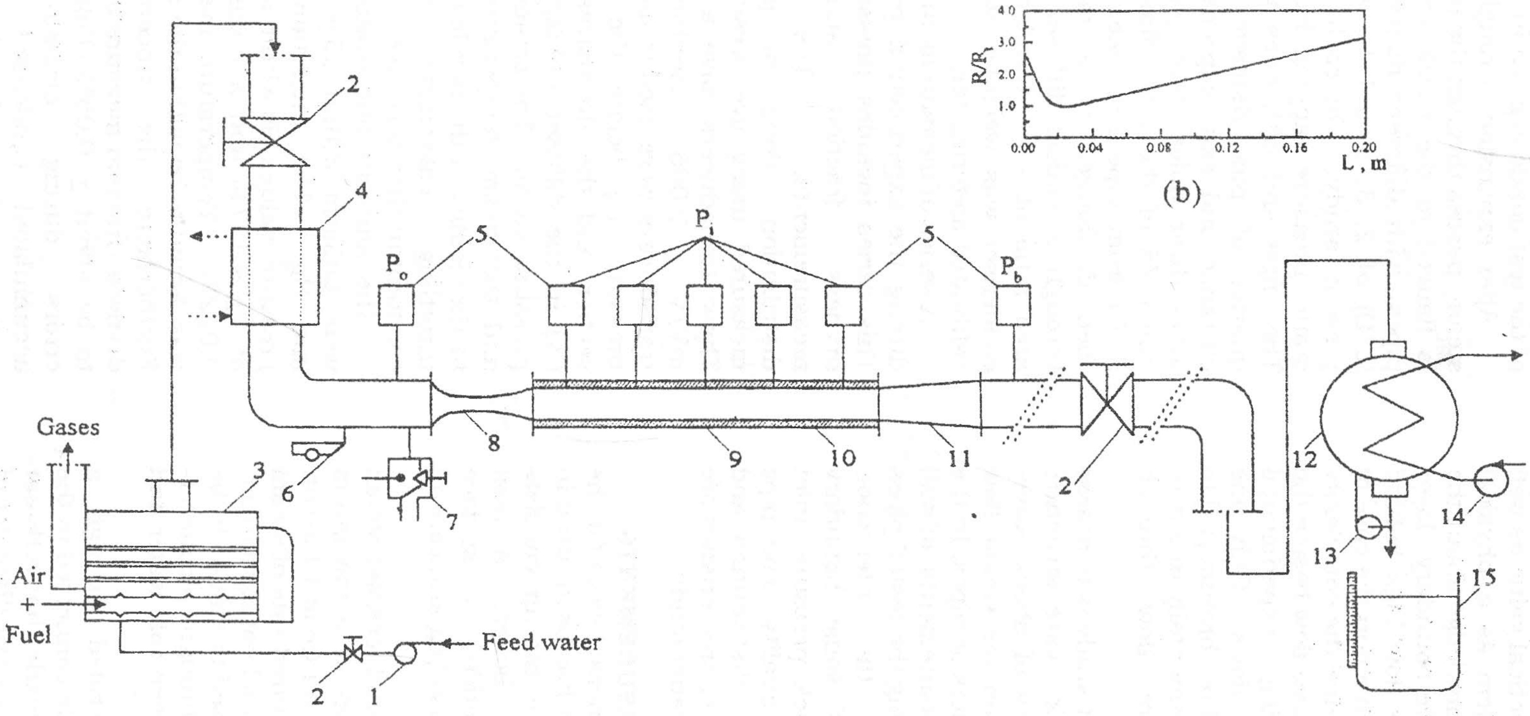
The fire-tube boiler produces wet steam of 0.995 dryness fraction at a maximum pressure of 6 bar and at a rate of 1 ton/hr. The boiler delivers the required rate of steam to the test section through a heat exchanger. The heat exchanger is used to diminish the steam dryness fraction through a counter-flow heat exchange between cold water and steam.

The steam is accelerated through a convergent-divergent nozzle connected to the main steam line. The nozzle has a throat diameter of 16 mm and an exit diameter of 50 mm which means that the ratio of exit to throat areas (A_2/A_t) = 9.766 and 2.34 exit Mach number for inviscid flow. Dimensions of the test nozzle is given in Figure 2-b.

After expansion through the nozzle, the steam passes through the tested pipe, which is flanged to the nozzle exit. Four tested pipes with different dimensionless lengths (L/D) of 2, 3, 5 and 10 were used in the present study. On each pipe length, five static pressure tapping holes were drilled. The first and fifth ones were spaced one quarter of pipe diameter from the pipe entrance and exit respectively. Whilst the other three holes were spaced at 0.25, 0.50 and 0.75 of the pipe dimensionless length (L/D) from pipe entrance. The steam was then discharged to a surface condenser through a conical diffuser having an overall area ratio of 4:1. Condensed steam in the condenser was weighted with the aid of a calibrated metering tank.

A series of measurements was carried out during the experimental part of this paper. This series includes pressure, temperature, dryness fraction and flow rate measurements. The static pressure distribution along the pipe length was measured using five pressure transducers. These transducers have a sensitivity of 1.0 mV/V ± 0.005. Another two pressure transducers were used to measure the intake pressure (P_o) before the nozzle entrance section and the downstream back pressure (P_b) in the diffuser tail pipe before the back pressure valve. The steam dryness fraction and the steam temperature were measured in the vicinity of the nozzle enterance using a throttling calorimeter and an iron-constantan thermocouple.

The ambient temperature and pressure were uniform within 35 ± 1 °C and 750 ± 2 mm Hg. The uncertainty in measured pressure values is within a maximum value of ± 0.177% and a minimum value of ± 0.022%. Temperature measurement error was found to be within the range of ± 5.03%. Furthermore, the uncertainty in steam dryness fraction measurement was obtained to be about ± 0.05%. Finally, the expected errors during measurement of the accumulated condensed steam by the metering tank were found within ± 3.33%.



1	Feed pump	6	Thermocouple	11	Diffuser
2	Pressure adjusting valve	7	Throttling calorimeter	12	Surface condenser
3	Fire-tube boiler	8	Convergent-divergent nozzle	13	Vacuum pump
4	Heat exchanger	9	Tested pipe	14	Circulating pump
5	Pressure transducer	10	Thermal insulation	15	Metering tank

(a)

Figure 2 General arrangement of the experminital setup a- Schematic diagram of instrumentation and measurments, b- Nozzle geometry.

RESULTS AND DISCUSSION

In presenting the current results, the test cases were chosen to span a reasonable range of the interaction characteristics through changing the boundary conditions within the following ranges:

i- back pressure values of 0.9, 1, 1.1 and 1.2 bar.

ii- initial pressure values of 3, 3.5, 4, 5 and 6 bar.

iii- initial wetness fractions of 0.5%, 2% and 4% for the supplied steam.

iv- dimesionless duct or pipe length (L/D) values of 2, 3, 5 and 10.

The remainder boundary conditions are listed clearly on each figure of the obtained results.

The distributions of wall pressure for different back pressure values in a pipe of dimensionless length (L/D) of 2 are presented in Figure 3. From this figure, one would basically notice the different locations of shock beginning [e.g.; shock begins at $x/D = 0.625$ for $P_b = 1$ bar, $x/D = 0.46$ with $P_b = 1.1$ bar and $x/D = 0.4$ when $P_b = 1.2$ bar] besides the variable shock strength. It should be noted for the wall pressure distribution along the tested pipe with a back pressure of 1.0 bar in Figure 3 that the pressure begins to increase at a distance of $x/D = 0.625$ behind the pipe entrance, continues to increase over a distance of about 1D and levels off to a plateau for the remainder pipe length. The trend of this pressure distribution agrees well with the previous measurements which were carried out in other situations. It is of great importance to note that, in these previous measurements which were reported by a lot of investigators (e.g., Petr [12] and Tan *et al.*, [18]) the shock wave was generated by a sharp-edged fin. However, the slight change in shock strength that was observed in Figure 3 is due to the interaction between the shock wave and laminer boundary layer [10]. It can be noticed further in Figure 3 that increasing the pipe back pressure causes both the shock strength and the shock wave-boundary layer interaction to be increased and at the same time to decrease the shock length.

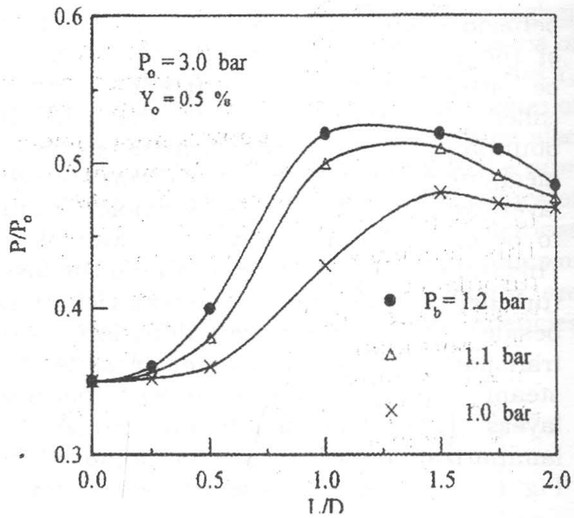


Figure 3 Effect of back pressure on the measured pressure distibution along a pipe (L/D=2)

The effect of steam initial pressure ahead of the nozzle entrance on the pressure distribution along the wall of a tested pipe with L/D equals 3 is shown in Figure 4. It can be observed from this figure that as the steam initial pressure (P_o) increases the shock moves further downstream along the pipe. Thus, the measurements in Figure 4 reveal that as P_o increases the socalled shock strength (i.e., dP/dx) was found to decrease. As can be concluded in the discussion of Figure 3, the pressure distributions with values of 4, 5 and 6 bar of the initial steam pressure affect the interactions between shock waves and laminar boundary layers. Whilst the pressure distribution which results from an initial pressure of 3 bar declares another interaction between a shock wave and a boundary layer. The last behavior of the pressure distribution (i.e., with P_o=3 bar) coincides with the interaction of a shock wave and a turbulent boundary layer. Here, it is of great importance to remember that the boundary layer is generally considered in the case of supersonic wet steam flow through a nozzle-pipe combination as a turbulent one. It is known as reported by Shapiro [10] that the pressure rise across an interacted shock with a turbulent boundary layer is quite rapid. This behavior is observed clearly with $P_o \doteq 3$ bar in Figure 4. But the unexpected behaviors which were obtained for the values of the initial pressure of 4, 5 and 6 bar can be attributed to the occurrence of the so called "laminarization of the turbulent boundary layer". Laminarization means the mechanism by which a turbulent boundary layer was found at higher Reynolds number to become laminar-like near the wall [19-20]. This tendency is presumed due to the loss of turbulence transport in the wall vicinity [20] beside the turbulence diffusion during transportation of samll water droplets of wet steam through the turbulent boundary layers [21]. The significant influence of laminarization occurrence is apparent from Figure 4 in expanding the interaction zone.

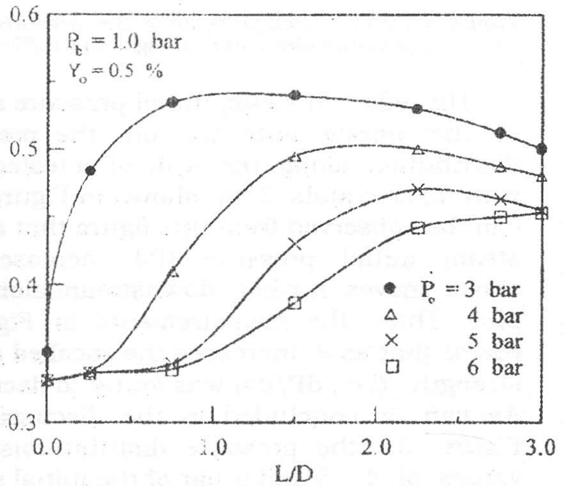


Figure 4 Effect of initial pressure on the measured pressure distribution along a pipe (L/D=3)

Figure 5 illustrates the effect of changing the steam quality ahead of nozzle inlet section on the wall pressure distribution along a nozzle-tail pipe of L/D=5. In this regard it can be seen that increasing Y_o moves the shock further in the downstream direction. This can be explained as Y_o increases, the boundary layer thickness increases resulting in a strong interaction, i.e. a weaker shock and lower pressure recovery are gained. Furthermore, it is clear also from Figure 5 that the pressure decays downstream in the redistribution zone. Moore [22] accounted for this pressure decay by the water droplet momentum dissipation through the interaction with the boundary layer which causes to decelerate the droplet and consequently creates a pressure decrease. In addition, vapor cooling due to droplet evaporation across the shock is considered as one of the pressure decay reasons.

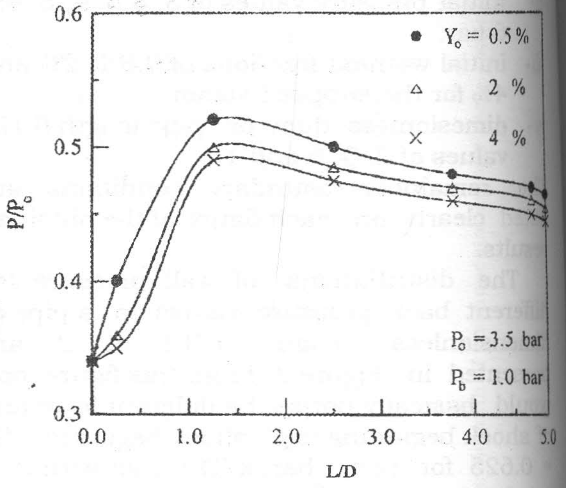


Figure 5 Effect of steam wetness fraction on the pressure distribution along a pipe of L/D=5

Variations observed in wall pressure profiles during steam flow through pipes with different dimensionless lengths (L/D), while the pipe diameter was kept constant, have been illustrated in Figure 6. From this figure, it can be noticed that increasing L/D moves the shock upstream towards the pipe inlet and converts also the interaction from a laminar one as seen with L/D = 2 and L/D = 3 to a turbulent one as shown with L/D = 5 and L/D = 10. This is because increasing the pipe length is accompanied with increasing its aerodynamic resistance. Furthermore, in the longer pipe; the boundary layer was found to be very thin before the interaction with a shock wave. This results in a strong shock. Therefore, for longer pipes or ducts the pressure was observed to be highly recovered in a longer distance beyond the shock location. But for shorter ducts which exhibit late shocks, the interaction completes slower and within a smaller distance after the shock position.

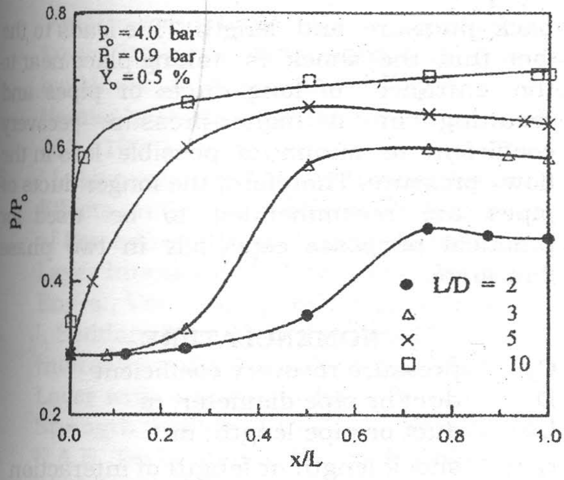


Figure 6 Effect of pipe length on the pressure profiles.

In the present study, the shock position (x_s) and the pressure recovery coefficient (C_p) are considered the parameters that describe the interaction characteristics. The shock position (x_s) is defined as the distance from the pipe or duct entrance section to the point where the pressure distribution starts to curve upwards. The pressure recovery coefficicent (C_p) is defined in Reference 5 as:

$$C_p = \frac{(P_{max}/P_o)-(P_i/P_o)}{1-(P_i/P_o)} \qquad (1)$$

It is worth mentioning here that both x_s and C_p are obtained directly from the measured wall pressure distributions [i.e from Figures 3 to 6]. Effects of changing P_b, P_o, Y_o and L/D on the interaction characteristics are given in Figures 7 to 10.

Generally, it should be mentioned from Figures 7 to 10 that the pressure recovery coefficient increases with increasing both of P_b and L/D, while it decreases with increasing P_o and Y_o. For the case of increasing C_p with increasing P_b, this is attributed to the fact that for small values of P_b the shock moves further downstream where the boundary layer is thicker and then after a strong interaction the pressure recovery becomes of small value. Increasing C_p with increasing L/D occurs primarily because in the longer pipes or ducts, where the boundary layer is still thin under turbulent condition, a weak interaction takes place. This weak interaction releases higher values of the pressure recovery. Reasons of C_p decreasing with increasing both P_o and Y_o are mentioned previously in the discussion of Figures 4 and 5. Figures 7 to10 indicate also that the shock moves further inside the pipe (i.e x_s increases) when the initial values of upstream pressure and steam wetness fraction are increased or when the values of pipe/duct back pressure and length are decreased. Explanations for these tendencies were presented above.

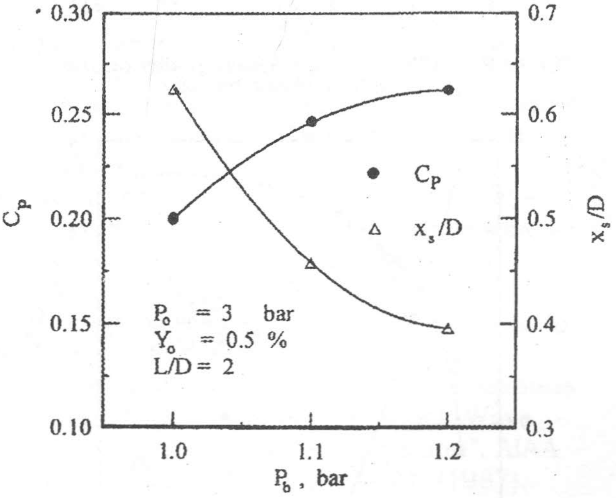


Figure 7 Effect of back pressure on the interaction characteristics.

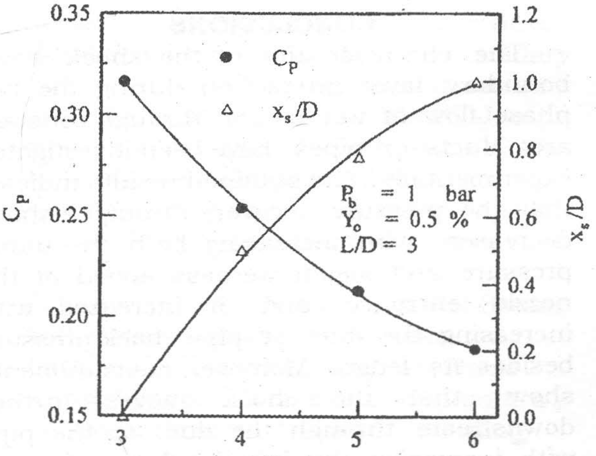


Figure 8 Effect of initial pressure on the interaction characteristics.

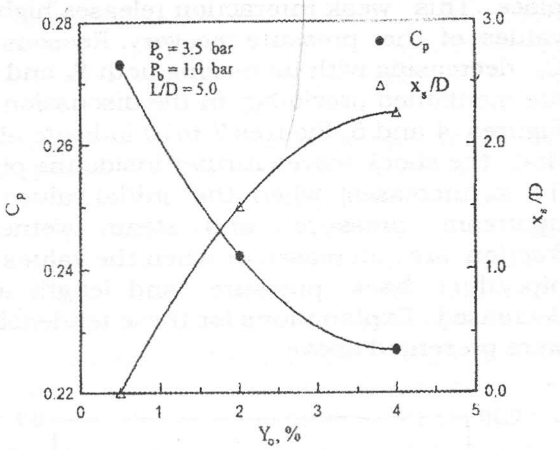


Figure 9 Effect of initial steam quality on the interaction characteristics.

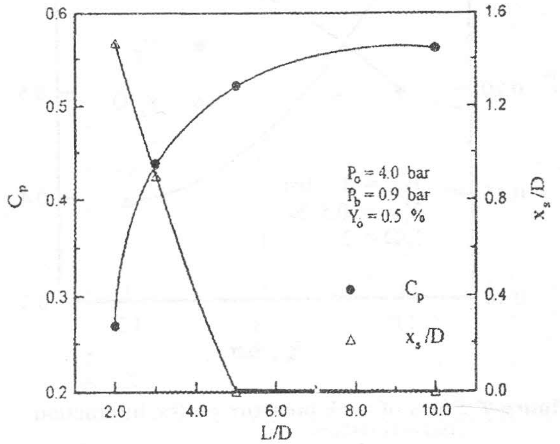


Figure 10 Effect of pipe length on the interaction characteristics.

CONCLUSIONS

The characteristics of the shock wave-boundary layer interaction during the two phase flow of wet steam through constant area ducts or pipes have been investigated experimentally. The obtained results indicate that the pressure recovery through a shock decreases with increasing both the initial pressure and steam wetness ahead of the nozzle entrance and it increases with increasing the duct or pipe back pressure besides its length. Moreover, measurements show that the shock moves further downstream through the duct or the pipe with increasing the initial values of steam pressure and wetness and it is further advanced towards the duct or pipe entrance with increasing the values of duct or pipe back pressure and length. This leads to th fact that the shock is taking place near t the entrance of long ducts or pipes an resulting in a higher-pressure recover coefficient or minimum possible loss in th flow pressure. Therefore, the longer ducts o pipes are recommended to be used fo practical purposes especially in two phas flow areas.

NOMENCLATURE

C_p	pressure recovery coefficient
D	duct or pipe diameter, m
L	duct or pipe length, m
ℓ_s	shock length or length of interaction region, m
P	static pressure, bar
R	radius of nozzle cross-section, m
x	coordinate, distance along the duct or pipe axis, m
x_s	shock position, m
Y	wetness fraction

Subscripts

b	back
i	refers to static pressure taps
o	initial
max	maximum
t	throat
2	nozzle exit

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دراسة لأنسياب فوق صوتى لبخار رطب متضمنا موجات صدمية خلال ممرات ثابتة المقطع
الجزء الأول: دراسة تجريبية

نبيل حنفى محمود
قسم هندسة القوى الميكانيكية- جامعة المنوفية

الملخص البحث

تهتم هذه الورقة بالدراسة التجريبية لبنية الموجات الصدمية المتضمنة داخل إنسياب فوق صوتى لبخار رطب خلال ممر ذو مساحة مقطع ثابتة أو أنبوب، يشتمل البرنامج التجريبى الحالى على قياسات للضغط عند الجدار على طول الممر أو الأنبوب المختبر، تم توجيه توزيعات الضغط المقاسة على طول الأنابيب المختبرة للحصول على الخصائص المميزة للتفاعل بين الموجة الصدمية والطبقة الجدارية، تم تنفيذ هذا البرنامج عند حدود شرطية مختلفة مثل قيم الضغط الأمامى (من ٣ : ٦ بار) والخلفى (من ١ : ١,٢ بار)– الحالة الإبتدائية للبخار المقدم (من ٠,٥ : ٤% درجة رطوبة) والشكل الهندسى للممر أو الأنبوب (نسبة طول الأنبوب إلى قطره من ٢ : ١٠) ، ولقد أوضحت النتائج التى تم الحصول عليها هنا أن هذه الحدود الشرطية تؤثر بخطورة على كل من بنية الموجة الصدمية والخصائص المميزة للتفاعل.