EXPANSION OF SUPERSONIC STEAM FLOW THROUGH A SUDDEN ENLARGEMENT

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ABSTRACT

An expansion of supersonic wet steam flow through a sudden enlargement duct has been studied for different flow parameters. The wet steam was firstly accelerated through a Laval nozzle and was then expanded in the duct. The expansion flow from the duct was discharged into the ambient air as a free jet. Measurements of the wall pressure along the duct wall were made for different stagnation pressure ratios, duct diameters, duct lengths as well as the initial wetness of supplied steam. The flow field of the free jet was also studied through flow visualization. The expansion of the wet steam through the sudden enlargement was compared to that of the air. The wall pressure develops from a negative value in the recirculating zone to be almost equal to the ambient pressure at the duct exit. A difference between the values of wall pressures for the air and steam flows in the recirculating zone is resulted. This is because the compression waves associated with supersonic steam flow propagate in a very complex media containing vapour and droplets. The gas dynamic characteristics of the sudden expansion steam flow depend on initial flow conditions and duct length as that of the air flow. The main behavior and general structure of a free jet of steam is almost the same as that of the air jet at the same conditions.

Key words: Sudden expansion, Wet steam, air flow, Wall pressure, Flow visualization, Separation flow, Compression waves, Droplets, Dryness fraction.

Nomenclature

C	choking velocity
d	nozzle diameter
D	duct diameter
L	duct length
p_a	ambient pressure
p_o	stagnation pressure
p_w	wall pressure
s	isentropic condition
x	distance along the duct length
x_o	initial dryness fraction of steam
ρ	fluid density

INTRODUCTION

High speed flows with sudden expansion are widely existed in various elements of thermal power station. Among these elements are two phase compact heat exchangers, steam generators, and emergency core cooling systems in nuclear reactors. The performance of such a flow regarding the gas dynamic characteristics has been studied by many investigators. Most of these studies have been considered a single phase flow. In 1776, Jean Charles Borda Wick [1] investigated the flow of water through a sudden increase of duct cross sectional area. Nusselt [2] seems to be one of the first to conduct experimental tests with high velocity gas flow (subsonic flow of air and steam) through a sudden increase in flow cross section. The most complete conceptual model of these flows was first proposed by Crocco and Lees [3] and restated in a simpler form by Chapman [4] and Korst [5]. But, little attempts were made to investigate the flow of two phase media (steam) in enlarged ducts.

The expansion of wet steam flows was studied by Young [6]. Bakhtar and Young [7] discussed the conditions of choking flow of wet steam. Narkis and Gal-OR [8] studied the two phase flow through normal shock waves. Two phase flow through nozzles at nonequilibrium state was also performed by Young [9]. The motion of saturated and wet steam through an enlarged duct was studied by Damazh et al [10]. In their study, the steam was flowed from a steam tube directly to an enlarged duct. The flow field associated with supersonic flows issuing into an enlarged duct is represented as given in Figure (1). The flow from the nozzle is suddenly expanded in the enlarged duct.

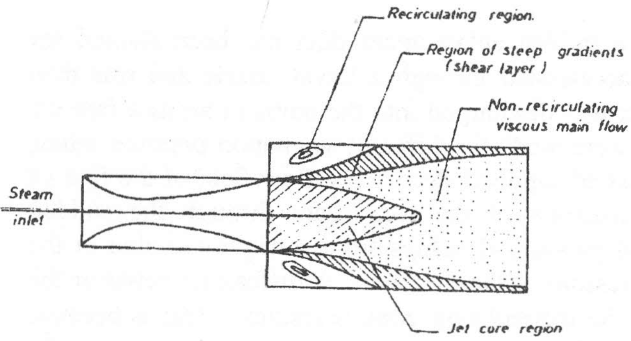

Figure 1. Flow field in a sudden expansion duct.

The flow separates from the step and a separated zone is formed in which a recirculating flow exists, the boundary of the jet, the potential core of the jet and equalization zone (viscous main flow). In the recirculating zone, systems of small vortices are generated and dissipated. The jet boundary is characterized by a very high swirl, caused by the nature of the gradient of the velocity field. In the equalization section, there is some restructuring of velocity field in the flow with a positive pressure gradient. Whereas, a negative pressure is usually evident in the separation zone. For large values of duct length, the propagation of compression waves and their reflection from the duct wall generates oscillation pattern flows inside the duct which strongly affect the pressure field.

The objective of the present work is to find out the characteristics of supersonic steam flow when expanding through an enlarged duct. The steam was firstly accelerated to supersonic speed through a supersonic Laval nozzle and was then expanded through the enlarged duct. The steam was then discharged into the ambient air as a free jet. The flow field of the free jet was photographed by a camera. The features of the expansion steam flow through the enlarged duct was compared with that of the air flow at the same conditions.

EXPERIMENTAL SET UP AND PROCEDURE

Figure (2a) shows a schematic diagram for the experimental apparatus used in the present work. A wet steam of various values of wetness fraction was generated by a fire tube boiler. The required rate and pressure of supplied steam were adjusted with the aid of pressure reducing valves. The wetness fraction of steam was varied via a heat exchanger which was located before the entrance to the nozzle. The steam was then accelerated through a Laval supersonic nozzle connected to the main steam line. The dimensions of the supersonic nozzle is given in Fig.2b. The steam from the nozzle was expanded in an axisymmetric enlarged duct. The inner diameter of the duct was chosen as 16 mm and 27 mm to give area ratios of 4 and 11. The area ratio is defined as the ratio between the tube cross sectional area to that of the nozzle exit.

Measurements of the main supply pressure, temperature and dryness fraction of the steam ahead of the nozzle entrance were made. The steam fraction and steam temperature were obtained using a throttling calorimeter and an iron constantan thermocouple. The steam pressure in the vicinity of the nozzle inlet was measured using a Bourdon tube pressure gauge. Wall static pressures along the enlarged duct was collected through pressure taps. These taps were connected to a multi U-tube mercury manometer. The steam from the enlarged duct was discharged into an ambient air as a free jet. The flow field of such a free jet was photographed for different inlet flow conditions. The total pressure at the nozzle inlet was ranged from 2 to 5 atmospheres. The tube length was chosen as 300, 175, 100, and 20 mm to change the length to duct diameter ratio. For accuracy, the ambient temperature and pressure were uniform within 35 ± 1 C° and 750 ± 1 cmhg. The uncertainty in the wall pressure was ± 0.6 % and the variation of total pressure at the nozzle inlet was uniform within ± 0.1 atmosphere. The uncertainty in the dryness fraction was ± 0.05 %. Finally, the variation of wall pressure of the steam along the duct length was compared with that of the air when expanding at the same inlet flow conditions in the same enlarged duct.

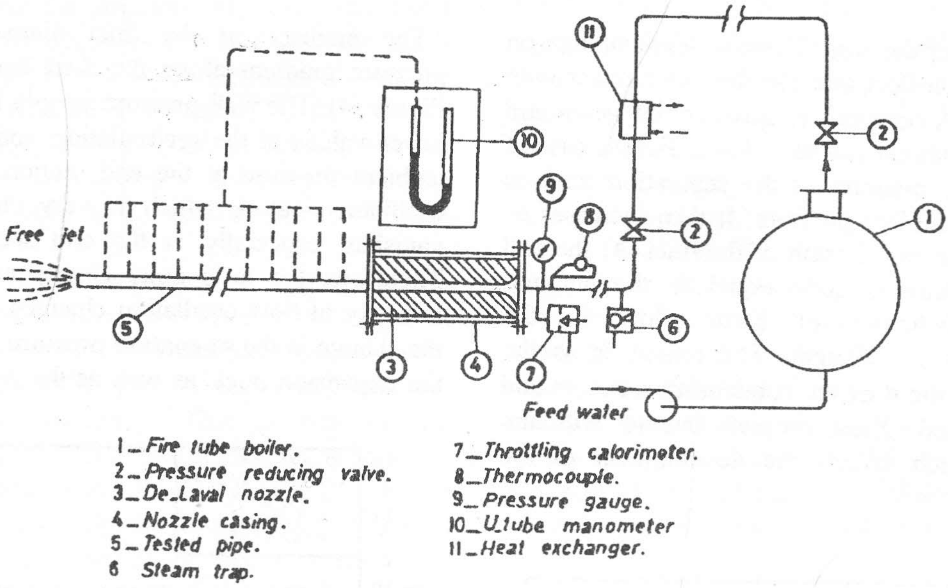

Figure 2a. Schematic of experimental apparatus.

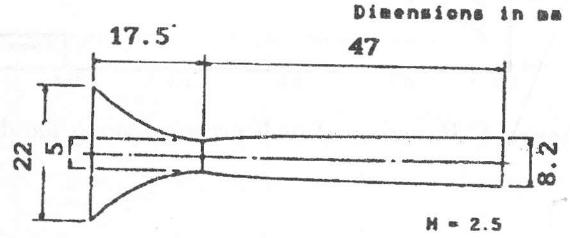

Figure 2b. Nozzle geometry.

RESULTS AND DISCUSSION

The results are given in the form of wall static pressure distributions along the enlarged duct length and flow visualization of the free jet issuing from the duct. The wall and stagnation pressures are made dimensionless with respect to the ambient atmospheric pressure.

At first, the supersonic flow was expanded with the range of stagnation pressure from 2 to 5 atmospheres. In this range, the nozzle was tested within the condition of overexpansion flow regime. Thus, it is important to note that the compression waves which occur at the nozzle exit propagate through the duct. In fact, when the fluid velocity exceeds the choking velocity of the two phase mixture significant shock associated losses occurs. The mass fraction of droplets in the mixture strongly affects the phase choking velocity. If one defines the two phase choking velocity as the homogeneous velocity of the mixture

$$C = \sqrt{\left.\frac{\partial p}{\partial \rho}\right|_{s}}$$

then in a dispersed flow, the mixture choked at a velocity well below the vapour choking velocity. This phenomenon is exhibited by the velocity at the throat of a convergent divergent two phase flow nozzle. Because the choking velocity is strongly affected by the mass fraction of the dispersed liquid droplets in the mixture, even relatively low velocity flows can be supersonic with respect to the two phase choking velocity. The formation and severity of a normal shock wave in a two phase mixture depends strongly on the coupling between phases - particularly droplet size. As the droplet size becomes smaller, the mixture behaves as a continuum, and sharp discontinuities can occur at velocities above the two phase choking velocity but below the sonic velocity of the vapour. The distribution of wall static pressure along the enlarged duct is given in Figure (3) for steam and air flows. The wall pressure oscillates along the duct length. The minimum pressure occurs at the recirculating zone. This minimum value depends on the stagnation pressure. After this zone, the wall pressure increases to be closer to the ambient pressure as the flow goes to the end. This oscillation in the pressure field is due to the shock waves which occur at the edge of the step. These shocks impinge on the wall and then reflect into the duct to interact with the main stream. A comparison between the steam and air flows can be summarized as follows: For the case of air expansion, the pressure at the separation zone is much below the ambient pressure. It then increases as moved towards the exit section of the duct. At the end section, the pressure is quite equal to the ambient pressure. The behavior of steam flow in the recirculating zone is different. The reason is as the steam expands in the duct the condensation occurs and droplets are formed. These droplets interact with the shock waves which affects the development of the pressure field.

The increase in the duct diameter changes the pressure gradient along the duct length, as shown in Figure (4). The wall pressure steeply increases from the lower values at the recirculating zone to be equal the ambient pressure at the end section of the duct. The oscillatory nature which is very clear in Figure (3) vanishes, especially at the end section of the duct. Therefore, the tests quite clearly confirmed that the intensity of flow oscillation changes very strongly with the change in the stagnation pressure, the dimensions of the expansion duct as well as the working media.

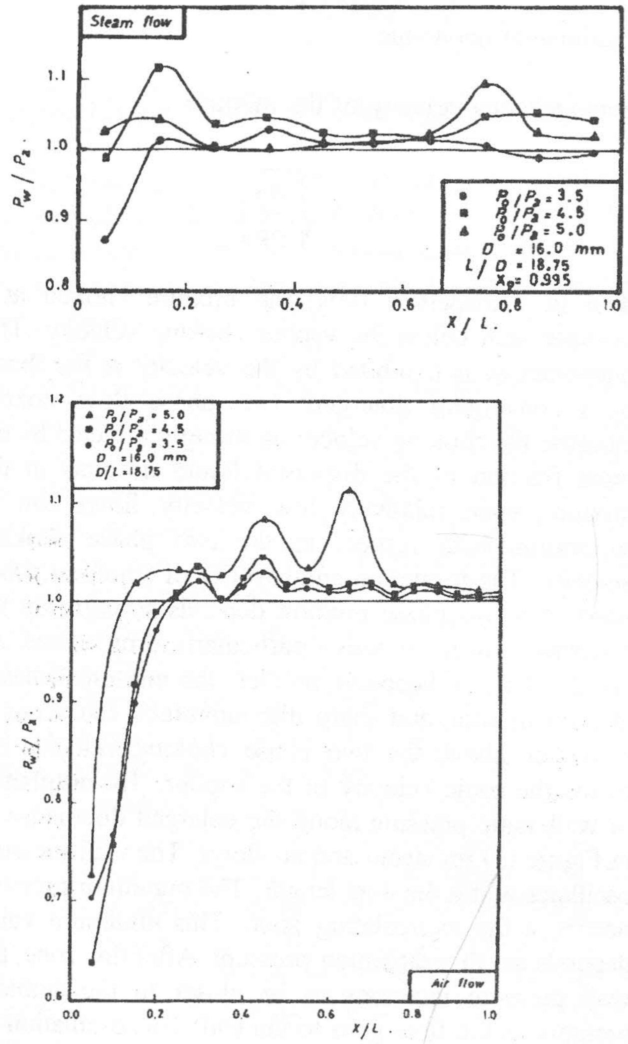

Figure 3. Variation of wall pressure along the duct.

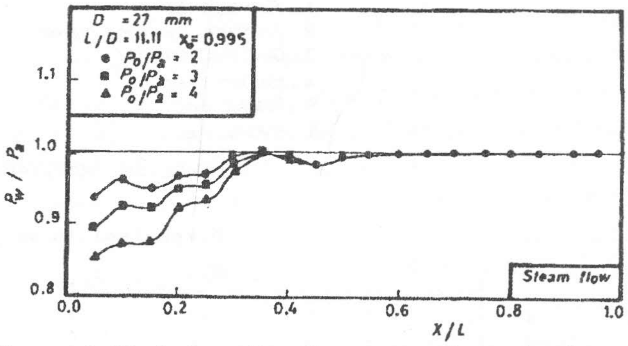

Figure 4. Variation of wall pressure along the duct.

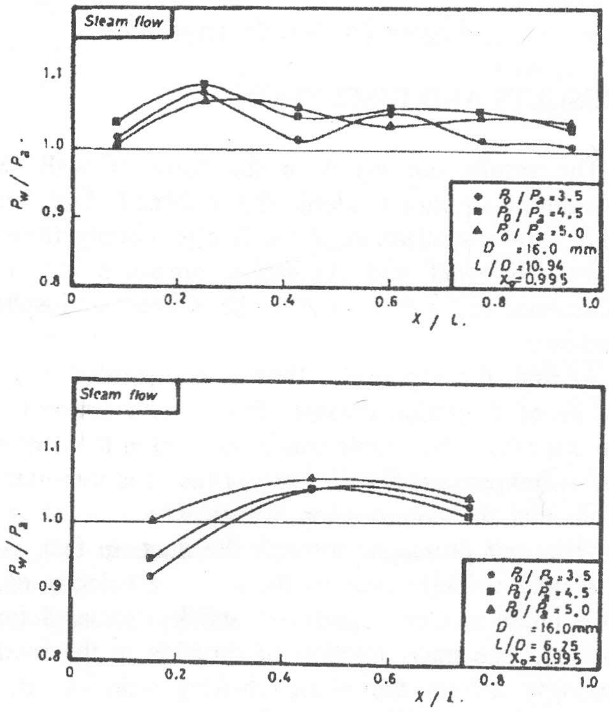

Figure 5. Variation of wall pressure along short ducts.

Figure (5) shows the structure of flow oscillations when reducing the duct length. In this case, the value of the wall pressure in the separation zone changes as the duct length is reduced. For short ducts, the pressure field needs more length to complete its development, to be equal the ambient pressure before goes to the atmosphere. This is due to the compression waves and formed droplets.

The effect of initial dryness of steam on the development of the pressure field through the long duct is given in Figure (6). The pressure just after the nozzle, in the separation zone is negative. Then, the pressure goes up suddenly. This is due to the compression waves which occur in the duct. The sharp decrease in the pressure at x/L = 0.2 may be due to the flow separation caused by the formation of droplets. The increase in the wetness of steam leads to an increase in the oscillatory nature associated with the pressure field.

For the short duct, the effect of the initial wetness of steam on the pressure field is significant as seen in Figure (7). The value of wall pressure in the separation zone is affected by the duct length. Also, the oscillatory nature associated with the flow field is very clear in this case. The flow field of the free jet issuing from the duct was photographed for the long duct (D = 16 mm, L/D = 18.75) at different stagnation pressure ratios, Figure (8). It is clear that the condensation occurs due to the expansion in the duct. The arrow indicates the width of the steam jet which was measured at the same distance from the end of the duct. The width of the jet changes with stagnation pressure. The jet of steam flow, in the general case, spreads as the air jet and the structure of the jet boundary is almost the same . Also, the propagation of the steam jet is similar to that of the air jet.

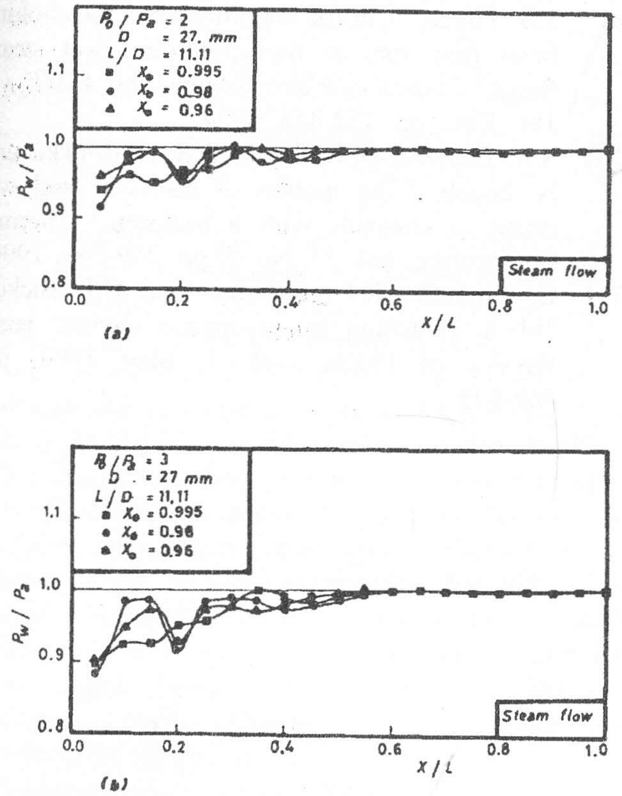

Figure 6. Effect of steam quality on wall pressure along the long ducts.

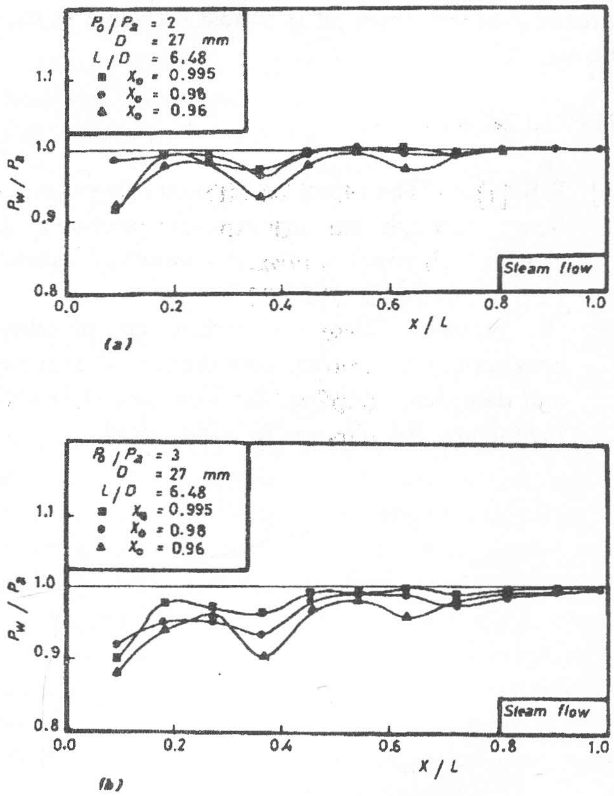

Figure 7. Effect of steam quality on wall pressure along the short ducts.

CONCLUSION

The flow field of supersonic steam expanding suddenly in an enlarged duct is studied experimentally through measurements of wall static pressures. The Flow visualization of the free jet issuing from the duct is given. It is found that the behavior of steam when expanding in the enlarged duct is slightly different from that of air at the same conditions. The main reason is the formation of droplets due to the condensation during the expansion process and the compression waves associated with the overexpended flow which propagate in the same direction of the droplets. The pressure field is affected by stagnation pressure ratio, the duct diameter, the duct length as well as the wetness fraction of steam at the inlet of the nozzle. The increase in the wetness of steam leads to a flow separation resulting an oscillatory nature in the pressure field. The photographs show that the propagation and spreading of the steam jet is almost the same as that of the air jet.

REFERENCES

[1] R.S Wick, "The effect of boundary layer on sonic flow through an abrupt cross sectional area change," *Journal of the Aeronautical Sciences*, Oct. pp. 675-682, 1953.

[2] W. Nusselt, "Der stossverlust an plotzlichen erweiterungen in rohen bein durchfluss von gasen und dampfen, "Zeitung fur Vereininger Deutches Ingenieurs, Bd. 73, pp. 763-764, 1929.

[3] L. Crocco and L. Lees, "A mixing theory for the interaction between dissipative flows and nearly isentropic streams, " *Journal of the Aeronautical Science,* vol. 19, No. 10, Oct. pp. 649-676, 1952

[4] D.R. Chapman, "An analysis of base pressure at supersonic velocities and comparison with experiment," *NACA TN*, No. 2137, July, 1950.

[5] H.H. Korst, "A theory for base pressure in transonic and supersonic flow," *Journal of Applied Mechanics*, vol. 23, pp. 593-599, 1956.

[6] J.B. Young, "The fluid mechanics of nonnucleating wet steam flows," Whittle laboratory report, No. TR 111, University of Cambridge, 1982.

[7] F. Bakhtar and J.B. Young, "A study of choking conditions in the flow of wet steam," *Proc. Instn. Mech. Engnrs.*, vol. 192, pp. 237, 1978.

[8] Y. Narkis and B. Gal-OR, "Two phase flow through normal shock waves," *Journal of Fluids Engineering ASME*, Sept. pp. 361-365, 1975.

[9] J.B. Young, "Critical conditions and the choking mass flow rate in nonequilibrium wet steam flows," *Journal of Fluids Engineering ASME*, vol 106, Dec., pp. 452-458, 1984.

[10] S.A. Damazh, M.E. Deich, D.S. Al'-Mul'ki, and N. Ismali, "The motion of saturated and wet steam in channels with a backstep," Thermal Engineering, vol. 37, No. 5, pp. 259-263, 1990.

[11] E. Gutmark, K.C. Schadow and C.J. Bicker, "Mode switching in supersonic circular jets," Physics of Fluids, vol. 1, May 1989, pp. 868-873.