Mansoura Engineering Journal

Volume 20 | Issue 1 Article 19

3-1-2020

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Recommended Citation

Slleem, Ahmed; Wahba, E.; and Naser, M. (2020) "An Experimental Investigation on Flow Field in a Dump Combustor Model.," *Mansoura Engineering Journal*: Vol. 20 : Iss. 1 , Article 19.
Available at: https://doi.org/10.21608/bfemu.2021.160939

AN EXPERIMENTAL INVESTIGATION ON FLOW FIELD IN A DUMP COMBUSTOR MODEL

بحث معملى لمجال السريان فى نموذج لغرفة إحتراق

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ملخص البحث :

فى هذا البحث تمت دراسة خصائص السريان معمليا فى نموذج لغرفة الإحتراق (Dump Chamber) . يتكون هذا النموذج من مدخل متسع فجائيا يليه غرفة إحتراق ذات مقطع مربع متصل بنهايتها بوق متقارب. تركز هذا البحث على إيجاد تأثير كل من : وجود البوق المتقارب فى نهاية الغرفة ، وطول الغرفة ، ورقم رينولدز علىّ توزيع الضغط على الجدار ، والضغط والسرعة عند خط المنتصف المحورى للغرفة (Centerline) ، وتوزيع السرعة فى الإتجاه العمودى على إتجاه السريان وكذا حجم وطول منطقة الدوامات. قورنت النتائج بمثيلاتها فى حالة عدم وجود البوق المتقارب فى نهاية الغرفة ، وقد أظهرت النتائج أن كلامن طول وحجم منطقة الدوامات وإعادة بناء السريان بعد منطقة السريان مماثلة لحالة عدم وجود بوق عندما يكون طول الغرفة ٨,٦٥ من إرتفاع العتبة عند المدخل. الدراسة أظهرت زيادة ملحوظة فى الضغط الجدارى قبل دخول البوق مباشرة وعلى النقيض إستمر الضغط الجدارى فى التناقص نتيجة لتأثير الإحتكاك اللزج فى حالة عدم وجود بوق متقارب. النتائج أظهرت أن منطقة إعادة بناء السريان التى تلى منطقة الدوامات تتقلص مع نقصان طول الغرفة. وجد أيضا أن منطقة الدوامات تنتهى داخل منطقة البوق المتقارب عندما يصل طول الغرفة الى ٤,٦٥ من إرتفاع العتبة عند المدخل. وظهر أيضا أن تأثير رقم رينولدز طفيف على توزيع الضغط الجدارى.

ABSTRACT:

The flow field characteristics in a dump combustor model is investigated experimentally in this paper. The model consists of a square cross-section area duct with a sudden enlargement chamber followed by a convergent nozzle. Attention is focused on finding the effect of nozzle existence at the end of the chamber, the chamber length, and the Reynold's number (based on the step height and inlet maximum velocity) on the wall pressure distribution, the axial centerline velocity and pressure, the velocity profiles, the recirculation zone size and the reattachment length.

The results are compared with the corresponding results when the nozzle is absent. The results indicate that the reattachment length, the recirculation zone, and the redevelopment after reattachment is almost the same in the case without nozzle and when chamber length is 8.65 step height with nozzle existence. The wall pressure exhibits a substantial increase just before the nozzle entrance, while it continues its decrease, in the case without nozzle, because of viscous friction. The results show also that the redevelopment zone following

the reattachment shrinks as the chamber length decreases. The reattachment occurs inside the nozzle when the chamber length becomes 4.65 step height. The change in Reynold's number shows a small effect on the wall pressure distribution.

1-INTRODUCTION:

The dump combustor basically consists of a sudden expansion from an inlet duct into a chamber followed by a nozzle. This type of comubstors is the typical combustor of ramjet engines, Yang et a. [1], Yu et al. [2]. The flow field formed by a rearward-facing step was the subject of research for the past three decades, Smyth [3], Moon et al. [4], Bach et al. [5], Kim et al. [6] are just a few. Some others are extended for compressible flow, e.g., Hayakawa et al. [7] and for stabilizing of flame as in Robert et al. [8]. The flow field in sudden expansion is characterized by flow separation, flow recirculation and flow reattachment. The turbulence produced in the recirculation zone enhances mixing between the fuel and oxidizer and results in a flame stabilization in dump combustors. The flow field may be divided into two main regions; the flow recirculation region and the main flow region, (Drewry [9]). The two regions are separated by a dividing stream line. The point at which the dividing stream line strikes the wall is called the reattachment point.

Factors that affect the recirculation zone size and the reattachment length include, among many, the step height, the flow Reynolds number, the existence of nozzle and the length of combustion chamber. In studying the effect of Reynolds number on the recirculation zone forming behind a rearward-facing step in a long channel, Ahmed et al. [10] found that the recirculation zone length increases with Reylonds number, reaching a maximum at transition and then decay to a shorter length at the turbulence range. In a study on the effect of cavity length between the sudden expansion and a sudden contraction sections in a dump combustor on mechanism of convective instability, Habib et al. [11] showed that the reattachment occurs on the down stream edge of the cavity before it reaches the bottom wall if the cavity length is short, in which the length to step height is less than 2, otherwise it impinges on the wall first, at high Rynolds numbers ($Re = U_m h/\nu > 1000$) where Um is mean velocity in the channel.

Yang et al. [1] found, in a configuration similar to the present configuration, that the nozzle existence decreases the reattachment length to 4.5 step height at Reynold number 6.4×10^4 (based on the inlet duct diameter and central velocity), and $L/h = 11.36$, compared with 6-9 step height found by Moon et al. [4], in a long duct without nozzle, in an abruptly expanding circular long duct without nozzle at Reynolds number ranging from 10^3-10^5. Drewry [9] found that reattachment length is 7.9 and 9.2 step height at Reynold's number 1.3×10^6 and 2.2×10^6, respectively. The reattachment length in a long pipe depends weakly on the Reynold'snumber if it is very large, as confirmed by Back et al. [5]. The excitation of the shear layer enhances the formation of vortical structure and reduces the reattachment length, especially for turbulent flow, as shown by Frederick et al. [12]. The results in [12] indicated that the wall pressure fluctuates at the reattachment zone and the fluctuations are more intense when the shear layer is exited. . The reattachment length was identified as the point where the streamwise velocity attains zero value in the reattachment zone at a distance y= 0.015 step height above the reattachment wall.

Kim et al. [6] studied the flow characteristics in the separated shear-layer, the reattachment zone and the redeveloping boundary layer after the reattachment in a long pipe. Two different step-heights are used. They showed that turbulent intensities and shear stress reach maxima in the reattachment zone, followed by a rapid decay near surface after reattachment. They showed also that the wall static pressure beyond the reattachment decreases. The reattachment length in this work was 7 step height. The numerical treatment of Gooray et al. [13] of turbulent recirculating flow beyond reaward-facing step in a long duct showed also that the reattachment length ranges from 5-8 step height. Recently, Syahril et al. [14], studied the effect of initial conditions on the reattachment length in backward facing step flow experimentally. Upstream of the step, they considered three configuration; namely canal case, divergent case and wall jet case and for smooth and rough walls. They showed that in the canal case large eddies impinge on wall and then sweep downstream the reattachment point. In divergent case, these eddies sweep downstream and upstream of the reattachment point. In the jet case, the eddies destroy all the traces of the upstream flow. The redevelopment of flow in the recovery zone is very affected by the wall roughness and by the turbulence in the external flow.

It is noticed that most of the previous works concentrated on the recirculation zone size and the reattachment length following the sudden enlargement in long ducts. Very little attention was given to the short ducts and to the existence of nozzle, even though its practical importance, particularly in ramjet dump combustors. Therefore, the present experimental work focuses on finding the effects of nozzle existence following the chamber, the chamber length, and the Reynold's number on flow field in the model; namely, the wall pressure distribution, the reattachment length, the centerline axial velocity and axial velocity profiles. The complications arise from the complex geometry, especially due to the nozzle existence, prohibited the numerical treatment of the problem, in the time being. Therefore, it will be certainly considered in the future.

2- EXPERIMENTAL SET-UP:

The experimental measurements were conducted in the test section of a subsonic wind tunnel of square cross-section area (30x30 cm). The wind tunnel is provided by a fan to withdraw air from atmosphere through a fine screen to break the disturbances and eddies. The sudden expansion is manufactured from two parts of wood with very smooth inner surfaces. One is fixed in the upper wall and the other in the lower wall of the tunnel test section at its entrance. These parts form a convergent duct followed by a constant area duct. The length of the convergent part is 20 cm and the length of the straight part is 20 cm. Therefore, the step height of the sudden enlargement is 10 cm. The sudden expansion section is followed by a chamber of square cross-section area (30x30 cm) and a convergent nozzle. The nozzle length is 20.5 cm and its exit cross-section area is 10x30 cm. The nozzle contour is shown in figure (1-a) with its equation. The distance between the sudden enlargement section and the nozzle inlet is allowed to vary by changing the nozzle location. The schematic diagram of the test section is shown in figure (1-b).

The wall pressure distribution is measured by a multi-tube manometer attached to tappings of 0.5 mm diameter drilled along the centerline of the bottom wall of the test section. The axial velocity was measured by a pitot-static tube. A transverse mechanism was used to allow velocity measurements in axial and transverse directions. The probe was calibrated and the relative error was found to be ∓ 0.1% in velocity measurements.

3- RESULTS AND DISCUSSION:

Three groups of results are presented here. (1) The effect of nozzle existence on the flow characteristics following the sudden expansion in the chamber and in the nozzle. (2) The effect of chamber length, in which three different chamber lengths are considered; namely 4.65, 6.65 and 8.65 step height. The Reynold's number (based on the inlet central axial velocity and step height) in the previous two cases was kept constant at $Re = 2.7\times10^5$ and the step height is constant at 10 cm. (3) The effect of changing Reynod's number, while keeping the chamber length and step height constants.

The wall static pressure distribution is presented in the form of pressure coefficient defined as follows;

$$C_p = \frac{p - p_o}{0.5\rho_o U_o^2} \qquad (1)$$

where, p_o, ρ_o and p are the atmospheric pressure and density and the measured static pressure, respectively. U_o is the axial inlet velocity.

In what follows, the velocity and distance are normalized with respect to the inlet axial velocity and the step height, respectively.

3.1 EFFECT OF NOZZLE EXISTENCE:

Figure (2) is a schematic diagram of the expected flow field regions in the present configuration. In region (I), a recirculation zone is formed following the sudden expansion and the reattachment of flow on the lower wall. Region (II), is a redevelopment zone in which viscous friction is dominant. Region (III) is another recirculation zone with a counter clockwise vortex generated due to the nozzle wall curvature.

The wall pressure distribution and the mean velocity profiles at different stations along the chamber will be given below.

3.1.1 WALL STATIC PRESSURE DISTRIBUTION:

The wall pressure distribution with and without nozzle existence is shown in figure (3). The chamber length between the sudden expansion section and the nozzle, L/h = 8.65 and the Reynold's number is 2.7×10^5. The two curves exhibit similar behavior up to X/h ≈ 6.5. In both curves the pressure decreases slightly up to x ≈ 1.8, followed by a steep pressure increase due to the sudden enlargement. It reaches a maximum then it decreases. The behavior is well known globally. The reattachment occurs presumably at almost x= 3.2 for the two curves. The shown pressure increase after the reattachment is due to the high turbulence in the reattachment zone which is confirmed by Gooray et al. [13], Yang et al. [1] and Kim et al. [6]. The noticed decrease after that is attributed to viscous friction in the developing flow. In the absence of nozzle, the pressure decrease continues. However, in the existence of nozzle, the pressure starts to increase again at X/h ≈ 6.5, before the nozzle entrance. This increase may be attributed to the flow separation caused by the nozzle wall curvature. The pressure reaches a stagnation value near the wall. Presumably the streamlines near the wall bends backward to form a counter clockwise vortex in the vicinity of the nozzle entrance, region (III) in figure (2). The pressure is maximum just at nozzle entrance. The pressure decrease in the convergent nozzle, following that, is a known fact. It is noticed that most of the expansion took place in the upstream part of the nozzle where the area changes rapidly, as shown in figure (1-a).

The shorter reattachment length here, 3.2 step height, compared with (6-9) step height, reported for examples in [4, 6, and 13] in a long duct after the sudden-expansion, may be attributed to the the three dimensionality in the present case.

3.1.2 THE MEAN AXIAL VELOCITY PROFILES:

The mean axial velocity variation normal to the chamber wall at different stations along the chamber has been measured using pitot-static probe. Even though the velocity measurements using single hole pitot-static probe in the recirculation regions are not reliable because the velocity direction changes from positive to negative continuously, the velocity measurement in the core region is reliable and can give us some insight on the core flow development. The velocity profiles shown in figure (4) for the case of L/h=8.65, indicate almost uniform velocity in the core region just after the sudden-expansion. A deviation from uniformity is seen after that. A decrease in the velocity magnitude as distance increases in the chamber is also seen with a noticed shift in the maximum velocity towards the lower wall which is a gravity effect, which is similar to the free jet. From these velocity profiles, it is expected that the reattachment occurs between X/h = 3 and X/h = 4 because the velocity measurement near the wall becomes positive. The velocity profile just after the exit nozzle is shown, as well.

3.2 THE EFFECT OF CHAMBER LENGTH:

The wall pressure, the centerline velocity and pressure variations at different chamber lengths are given below.

3.2.1 THE WALL PRESSURE DISTRIBUTION:

Figures (5-6) show the wall static pressure distribution for chamber lengths 6.65 and 4.65 step height, respectively. It is noticed, by consulting figure (3) in which L/h = 8.65, that as the nozzle becomes closer to the sudden-expansion section, the redeveloping region (II) shrinks. In figure (5); L/h =6.65, the reattachment is slightly shorter than that shown in figure (3); L/h = 8.65 and it is seen that the pressure continues its increase following the reattachment up to the nozzle entrance. Here, there is no space for flow development after reattachment. Instead, the flow separation near nozzle entrance causes a continuous pressure increase. In figure (6), where the chamber is shorter, L/h = 4.65, it seems that the reattachment occurs inside the nozzle because the pressure continues its increase, even inside the nozzle. Therefore, the pressure increases sharply because of the combined effect of pressure increase due to the high turbulence following the reattachment and that due to the flow separation near nozzle entrance. Figure (7) shows the wall pressure distribution for the three considered chamber lengths, in addition to the case without nozzle at the same Reynold's number. This figure shows also that, the reattachment length for the L/h = 4.65 is greater.

3.2.2 THE CENTERLINE AXIAL VELOCITY AND PRESSURE VARIATIONS:

The axial centerline velocity for different chamber lengths and also for the case without nozzle is shown in figure (8). It is worth to note that, the centerline velocity remains almost constant up to X/h = 2 for all cases. Then it starts to diminish with different rates after that. The figure illustrates, also that the centerline velocity diminishes faster in the case without nozzle and the diminishing becomes smaller as the chamber length gets smaller.

The centerline pressure distribution shown in figure (9) demonstrates that the largest pressure occurs in the case without nozzle, while it attains smaller values as the chamber length decreases in the existence of nozzle particularly after reattachment. However, in the recirculation zone, region (I), the pressure measurements show uncertainties. The results in figures (8-9) explain the core flow field in which the velocity decreases and the pressure increases with distance in all cases including the case without nozzle. Nevertheless, the nozzle existence causes a resistance to the flow expansion and this resistance becomes higher as the nozzle gets closer to the sudden enlargement section. This observation could be confirmed by comparing the centerline axial velocity, for example at X/h = 4.5 shown in figure (8) in which one can see that the velocity gets higher as the nozzle gets closer to the sudden expansion. The corresponding centerline pressure in figure (9) helps to confirm this conclusion.

3.3 THE EFFECT OF REYNOLD'S NUMBER:

Here, both the step height and the chamber length are fixed at 10 cm and 86.5 cm, respectively and the Reynold's number is allowed to vary.

In laminar flow over a sudden enlargement, Ahmed et al. [10], showed that the reattachment length increases with an increase in the Reynold's number. None the less, the reattachment length decreases again as the flow becomes turbulent. The present results, in which the flow is turbulent, the change in Reynold's number was found to have no effect on the wall pressure distribution or the reattachment length when Reynold's number changes from $2.8x10^5$ to $2.5x10^5$. However, the wall pressure decreases slightly when Reynold's number becomes $2.13x10^5$ as seen in figure (10). Gooray et al. [13] stated that" in turbulent flow, when the reattachment length is normalized by step height, Reynold's number has no effect". This statement confirms our results. The centerline pressure distribution given in figure (11) shows that the pressure increases with the decrease in Reynold's number, particularly, after reattachment.

4. CONCLUSIONS:

The present results indicate that the nozzle existence produces a separation zone characterized by an increase in pressure before the nozzle entrance. The redevelopment zone following the reattachment diminishes as the nozzle gets closer to the sudden enlargement section. The reattachment took place inside the nozzle when the chamber length becomes as small as 4.65 step height. The Reynold's number was found to have tiny effect on wall pressure distribution or the reattachment length in the turbulent flow. The centerline axial velocity decreases , in all cases, with distance along the chamber, but the rate of decrease is greater as the chamber length increases.

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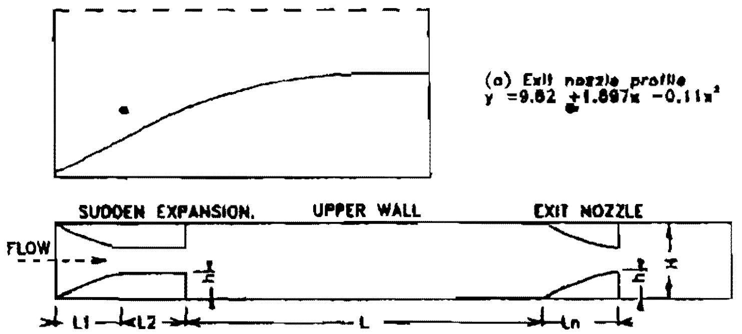

(a) Exit nozzle profile $y = 9.82 + 1.897x - 0.11x^2$

(b) Schematic diagram.

FIG.(1) THE CONFIGURATION OF THE TEST SECTION (L1=20 cm,L2=20 cm L=46.5 :86.5 cm, AND Ln=20 cm).

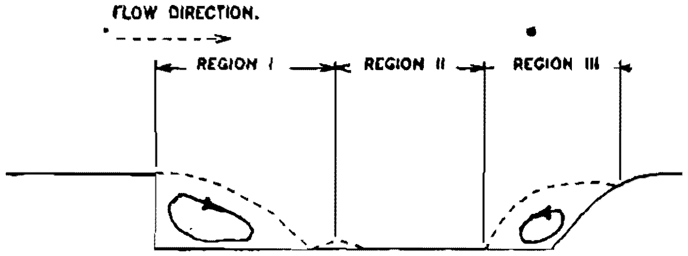

FIG.(2) FLOW PATTERN THROUGH THE TEST SECTION .

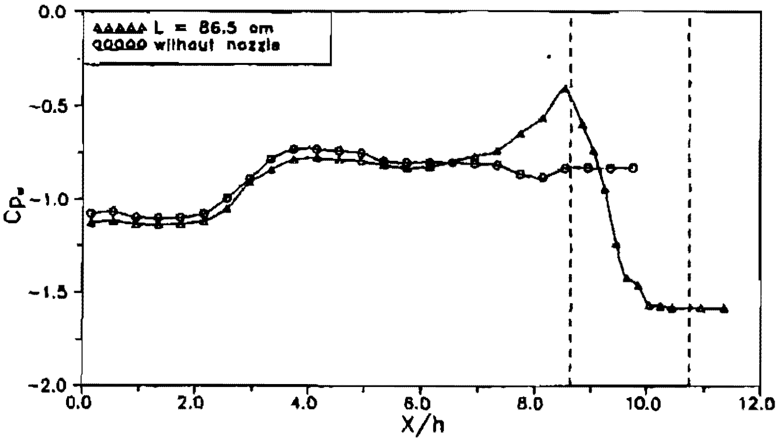

FIG.(3) WALL PRESSURE COEFFICIENT VERSUS DISTANCE FOR $Re=2.7*10^5$

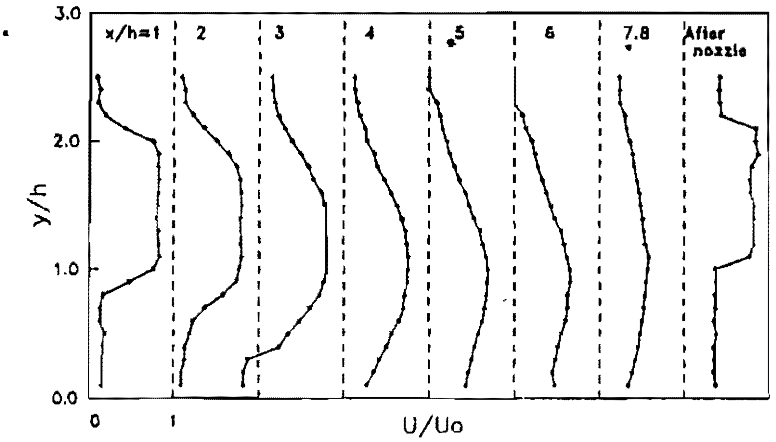

Fig.(4) THE AXIAL VELOCITY PROFILES AT DIFFERENT STATIONS ALONG THE TEST SECTION FOR S=86.5 cm & Re=2.7 *10^5

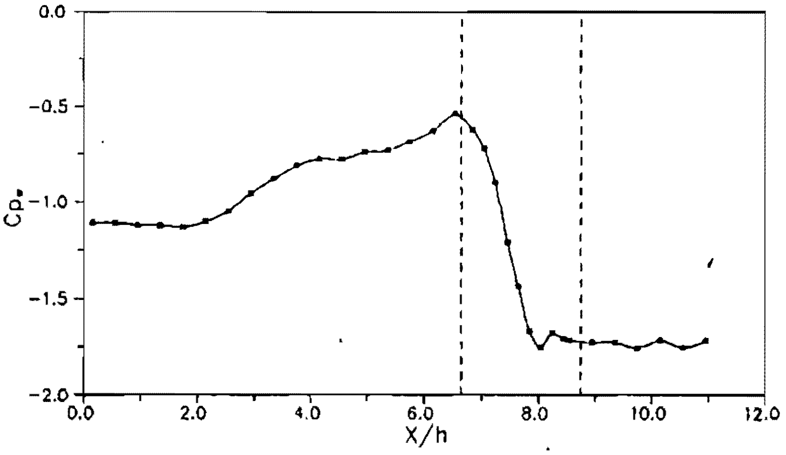

FIG.(5) WALL PRESSURE COEFFICIENT VERSUS DISTANCE FOR L=66.5 cm. &Re=2.7*10^5

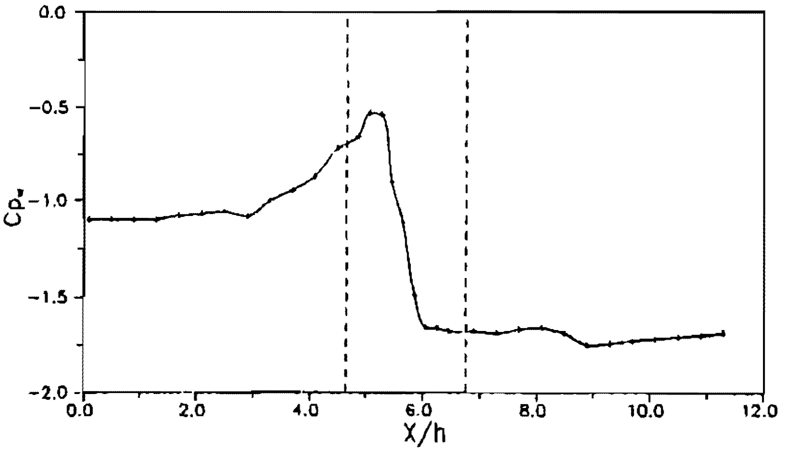

FIG.(6) WALL PRESSURE COEFFICIENT VERSUS DISTANCE FOR L=46.5 cm &Re=2.7*10^5

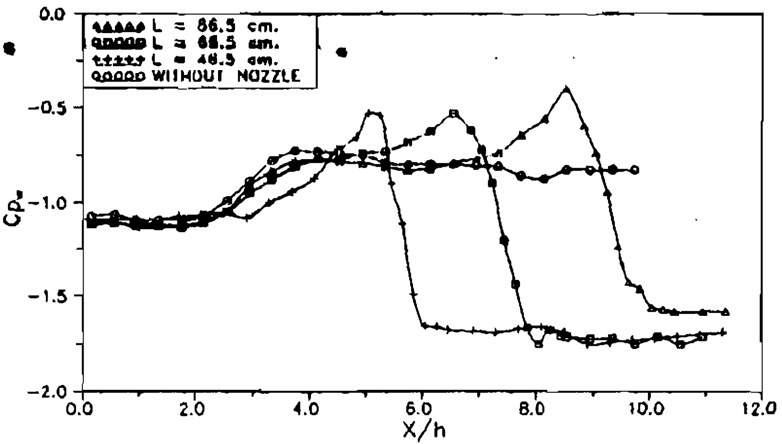

FIG.(7) WALL PRESSURE COEFFICIENT VERSUS DISTANCE FOR Re $=2.7*10^5$

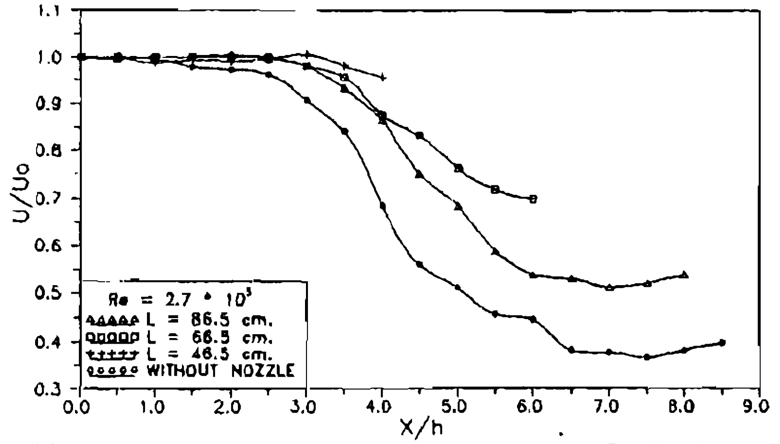

FIG.(8) AXIAL CENTERLINE VELOCITY VERSUS DISTANCE AT DIFFERENT CHAMBER LENGTHS.

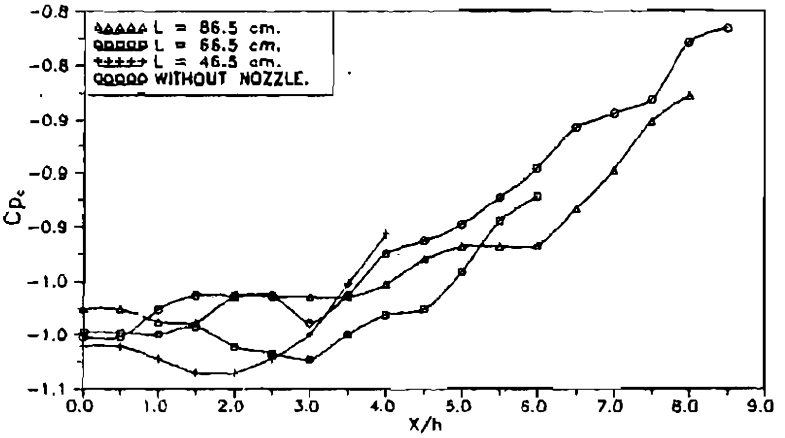

FIG.(9) CENTERLINE PRESSURE COEFFICIENT VERSUS DISTANCE FOR Re$=2.7*10^5$

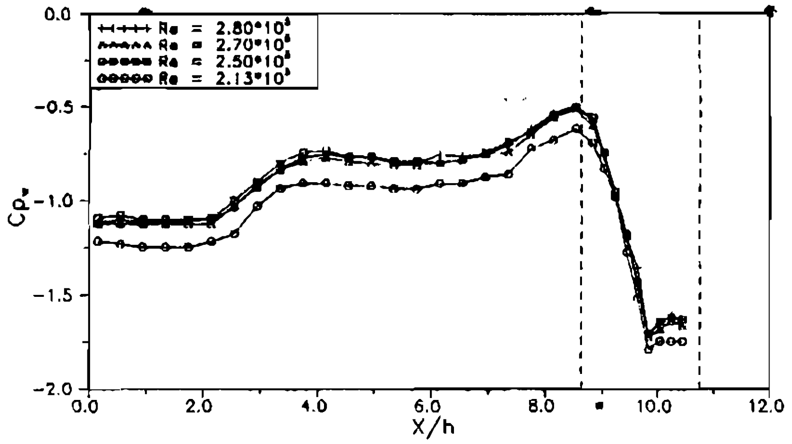

FIG.(10) WALL PRESSURE COEFFICIENT VERSUS DISTANCE FOR L=86.5 cm AT DIFFERENT REYNOLD'S NUMBER.

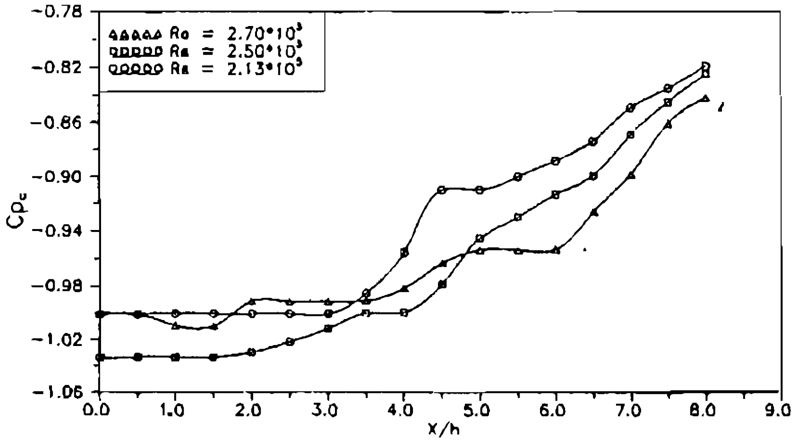

FIG.(11) CENTERLINE PRESSURE COEFFICIENT VERSUS DISTANCE FOR L=86.5 cm.