Chapter 1
INTRODUCTION

Diffusers are one of the standard challenges in fluid mechanics. The task of a diffuser is to decelerate the flow and to regain total pressure. It is more difficult to arrange for an efficient deceleration of flow than it is to obtain an efficient acceleration.

Diffusers play a vital role in many fluid machines to convert kinetic energy into pressure energy. The efficiency of this conversion process is important as it affects the overall performance of the machine. The pressure recovery, which is the measure of performance of diffusers, depends on many geometrical and dynamical parameters. Some geometrical parameters that govern the performance of a diffuser are inlet length and size of the duct, area ratio of the diffuser, angle of expansion, length of the diffuser, shape of the exit duct with free or submerged discharge conditions, etc. The dynamical parameters are inlet velocity profile, boundary layer parameters, Reynolds number, Mach number and so on. In the present work, two parameters namely inlet velocity profile and the geometry of the diffuser were selected in order to study their effects on the flow structure and performance of annular diffusers. Swirling flow in the diffuser plays an important role in controlling the flow separation and therefore the performance of the diffuser. Consequently, increased attention is being paid to the prediction of the swirling flow characteristics in the diffuser in order to optimize design. It has been realized that flows in the annular diffusers are strongly dependent on the geometries of the inlet and outlet conditions. Past numerical studies have rarely included inlet systems because of their complexities and thus simplifying assumptions and,' or experimental data are used to supply the inlet boundary conditions.

They reported that performance of annular diffuser having parallel diverging hub and casing was improved on the introduction of swirl. The optimum swirl angle was between 20°and 30°. They found that further increase in swirl degraded the performance of diffusers. Moreover, the present Thesis addresses the aforementioned issues and makes a systematic study of the influence of the inlet velocity component profiles (addressing the effect of the shape and the ratio of (averaged) radial to axial velocity) and outlet boundary conditions on the flow characteristics in the Annular Diffuser.

Diffusers are extensively used in centrifugal compressors, axial flow compressors, ram jets, combustion chambers, inlet portions of jet engines etc. The energy transfer in these turbo machineries involves the exchange of significant levels of kinetic energy in order to accomplish the intended purpose. As a consequence, very large levels of residual kinetic energy frequently accompany the work input and work extraction processes, sometime as much as 50% of the total energy transferred. A small change in pressure recovery can increases the efficiency significantly. Therefore diffusers are absolutely essential for good turbo machinery performance.
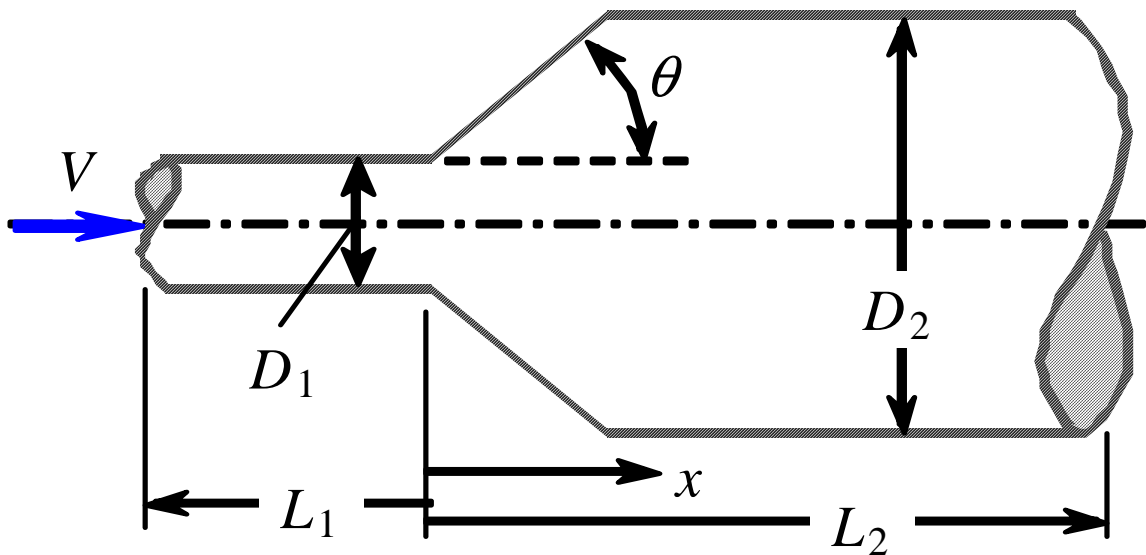

Fig.1 CONICAL DIFFUSER

1.1 Axial Diffuser –

In axial diffusers, fluid flows along the axis of diffusers and there is continuous retardation of the flow. Axial diffuser is divided in to the following categories-

➢ Conical diffuser

- ➢ Channel diffuser
- ➢ Annular diffuser

The basic geometric parameters for these types of diffusers are as follows:

1.1.1 For conical diffuser-

Non dimensional length, L/W_1

Aspect ratio, $AS = b/W_1$

Area ratio, $AR = A_2/A_1$

$$AR = 1 + 2\left(\frac{L}{W_1}\right)\tan\theta$$

1.1.2 For channel diffuser-

Non dimensional length, L/D_1

Area ratio, $AR = A_2/A_1$

$$AR = \left[1 + 2\left(\frac{L}{D_1}\right)\tan\theta\right]^2$$

1.1.3 For annular diffuser-

Non-dimensional length, $L/\Delta r$ or L/h

Area ratio, $AR = A_2/A_1$

$$AR = \left[1 + 2\left(\frac{L}{h_1}\right)\sin\theta\right] \qquad \text{(For equiangular case)}$$

1.2 Radial Diffuser

In radial diffusers fluid flows in radially outward direction in confined space between the two boundaries. Diffuser used in radial turbo machinery fall under this category. They may be vane less and vaned types. unlike the axial diffuser, this type of diffuser may convert kinetic energy into static pressure rise by one or two principles – an increases in flow passage area in order to bring about a reduction in the average velocity; – a change in the mean flow path radius to bring about a recovery in angular velocity according to the conservation of angular momentum.

1.3 Curved Wall Diffuser

In recent time most of the aircrafts use curved wall diffuser. In aircraft engines several modifications may introduce non-uniformities and higher level of turbulence in flow field entering the diffuser. In addition mechanical and structural requirement place

limits on the length of the passage. Curved wall diffuser is useful in this case and compatible with downstream requirement of flow besides it, these diffuser are also of fundamental and practical interest for various other applications like gas turbine system.

Curved diffusers are broadly classified as –

- ➢ 90 or part turn diffuser or half diffuser.
- ➢ 180 or U- diffuser.
- ➢ S- Diffuser.
- ➢ Y-Diffuser.

1.4   ANNULAR DIFFUSER

For decades researchers have paid more attention to conical diffuser and channel diffuser than to annular diffusers. But, the annular diffusers have a very strong industrial significance and have received attention in recent years. These types of diffuser are very much used in aircraft applications. With the help of annular diffuser the maximum presser recovery is achieved within the shortest possible length. With annular diffuser, good performance is possible with large wall angles since an inner surface is present to guide the flow radially outward. The annular diffuser affords the possibility of introducing many different geometric combinations since there is now an inner surface that can be varied independently of the outer surface. It is more difficult to define the essential geometric parameters for annular diffusers since the numbers of independent variables are large. The essential variables to define the geometry of annular diffuser are two wall angles, area ratio, non-dimentional length and inlet radius ratio. As the number of variables increases, geometry becomes more complex. By suitable combination of these variables we can find out number of geometry. The present study investigates the equiangular type of annular diffuser. In these types of annular diffusers both hub and casing are diverging outward with same angle of divergence.A survey of diffuser research has revealed that considerably more investigations have been carried out on two dimensional and conical diffusers. Much of the extent data covering annular diffusers was done in the experimental laboratory Stafford and James [1957]. But, the annular diffusers have a very strong industrial significance and have received attention in recent years. These types of diffuser are very much used in aircraft applications. With the help of annular diffuser the maximum presser recovery is achieved within the shortest possible length. With

annular diffuser, good performance is possible with large wall angles since an inner surface is present to guide the flow radially outward. The annular diffuser affords the possibility of introducing many different geometric combinations since there is now an inner surface that can be varied independently of the outer surface. It is more difficult to define the essential geometric parameters for annular diffusers since the numbers of independent variables are large Goebel and Japikse [1981]. The essential variables to define the geometry of annular diffuser are two wall angles, area ratio, non-dimensional length and inlet radius ratio. As the number of variables increases, geometry becomes more complex. This has not been economically possible by experiments and hence led to the development of computational fluid dynamic methods to analyze the performance characteristics of annular diffuser Arora, Pathak and Singh [2005].
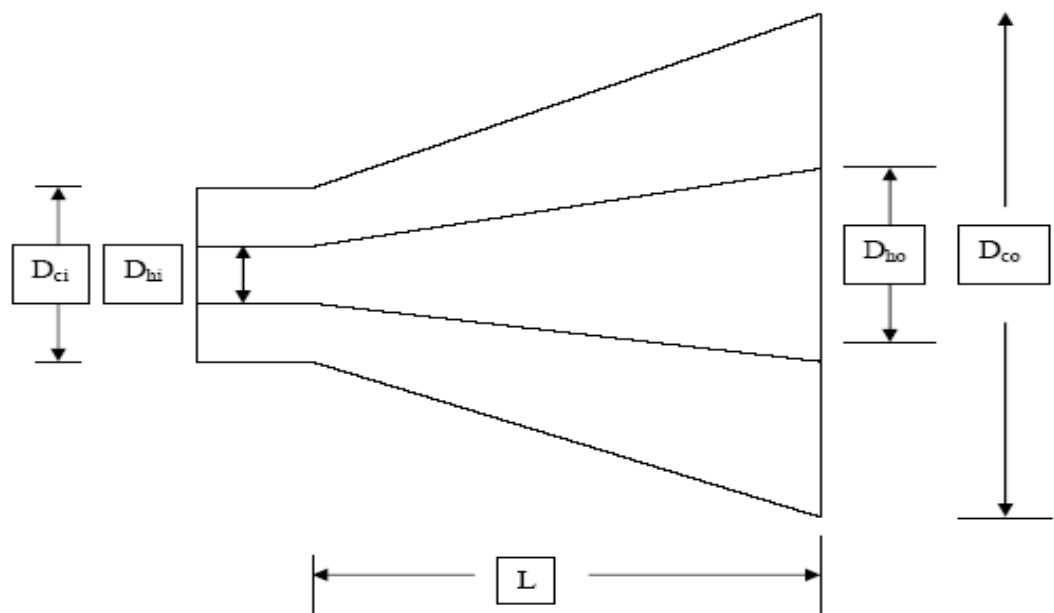
Fig.2 Annular Diffuser

1.5   Diffuser performance parameter

1.5.1   Geometric parameters

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Any duct geometry with an increasing area in the stream wise direction constitutes subsonic diffuser geometry. Therefore, the number of different diffusers geometries that can be conceived is infinite. However in practice, adequate design data are available for a limited number of geometries.

1. Rectangular cross section or planner diffusers
2. Conical diffusers
3. Straight walled annular diffusers

Other commonly used diffuser geometries include the radial and axiradial diffusers which are used at the exit of radial and axial turbo machines, respectively. These geometric parameters can be consolidated to a few non dimensional parameters that are found to be important in terms of diffuser performance. The first is the area ratio, AR, the area ratio of diffuser exit to inlet areas. The area ratio is measure of the theoretical diffusion or pressure recovery expected. The second important parameter is the dimensionless diffuser length define as : N/Wi or L/Wi for planar diffusers, N/ Ri or N/Ri for conical diffusers, and L/(Rit - Rih) , for annular diffusers. This dimensionless diffuser length in combination with the area ratio AR is measure of the overall pressure gradient expected across the diffuser. The third geometric parameter commonly used in displaying diffuser performance is the wall divergence angle--20 for planar and conical diffusers and 6 and 9h' for annular diffusers. The divergence angles, length, and area ratio are related as follows [10].

1.5.1.1 Aerodynamic blockage

Thin inlet boundary layers tends to be beneficial to high diffuser recovery and those longer diffusers necessary to achieve high levels of recovery as the inlet boundary thickness increases as stated by Hoadley D,et.al, 1969.

The blockage is the fraction or percentage of the inlet passage area which is occluded the boundary layer displacement thickness on all walls. The displacement thickness is taken as equal on all surfaces and then the following relationships ensue:

B = 2*/h for annular diffusers where h is annular height at inlet

B = 2*/D_1 for conical diffusers with uniform inlet boundary layers

1.5.1.2 Reynolds number:

Viscosity is an important parameter in any fluid dynamic process and normally appears in the form of a Reynolds number. Diffusers are characterizes by Reynolds

number based on an inlet hydraulic diameter. Shaalan, et al [1975] studies reported in this field suggest that the Reynolds number is a comparatively weak parameter as long as the flow is fully turbulent regime.

1.5.1.3 Inlet Mach number:

The Mach number at the inlet to the diffuser was thought to be important at values as low as approximately 0.7 and performance to fall off past this point. No significance on Mach number develops at throat for Mach numbers of less than 1.0 is studied by Thayer E B, [1971].

1.5.1.4 Inlet Turbulence intensity

The turbulence intensity is most frequently defined as an RMS value:

$$Tu = \frac{\left[\frac{1}{3}\left(u'^2 + v'^2 + w'^2\right)\right]^{\frac{1}{2}}}{U}$$

This equation defines the parameter most frequently used to specify the over all level of inlet turbulence intensity is given by Shaalan, et al [1975].

1.5.1.5 Effect of Compressibility:

With compressible flow both area, A, and density, p, increases with passage down the diffuser so that the reduction in velocity V, will be greater than in the case of incompressible flow where only the cross sectional area increases. It therefore follows that the pressure recovery coefficient should also be greater.

$$v = \frac{m}{\rho.A}$$

The rate of increase in value of Cp is not rapid until Mach number of 0.6 have been exceeded and than the effect is most pronounced when area ratios are low. These low area ratios correspond to the diffuser inlet vision and flow separation would therefore occur here as a result of predicted increasing adverse pressure gradient caused by the higher subsonic inlet mach number.

1.5.2   Design Performance Parameters

Performance parameters are very helpful in designing and predicting the performance of diffusers. These parameters reveal that diffuser geometry will give the desire

output or not. The following parameters are important to find out diffuser performance.

1.5.2.1 Static Pressure Recovery Coefficient

The pressure recovery coefficient of a diffuser is most frequently defined as the static pressure rise through the diffuser divided by the inlet dynamic head

$$C_p = \frac{p_2 - p_1}{\frac{1}{2}\rho v^2_{av1}}$$

where subscripts 1 and 2 refers to diffuser inlet and outlet conditions respectively. V_{avi} represents the average velocity at the inlet. An ideal pressure recovery can be defined if the flow is assumed to be isentropic. Then, by employing the conservation of mass, this relation can be converted to an area ratio for incompressible flow

$$C_p = 1 - \frac{1}{AR^2}$$

1.5.2.2 Diffuser Effectiveness

The diffuser effectiveness is simply the relation between the actual recovery and the ideal pressure recovery.
$$\eta = C_p \Big/ C_{pi}$$

This is an excellent parameter for judging the probable level of performance when it is necessary to estimate the expected performance under unknown conditions, relative to available data.

1.5.2.3 Total Pressure Loss Coefficient

The total pressure loss coefficient reflects the efficiency of diffusion and drag of the system. The most common definition of loss coefficient is as the ratio of total pressure rise to the diffuser inlet dynamic head.

$$K = \frac{\overline{p}_{01} - \overline{p}_{02}}{\frac{1}{2}\rho v^2_{av1}} \qquad\qquad K = \frac{\left(\overline{u}_1^2 - \overline{u}_2^2\right)}{U_i^2} - C_p = \left(\alpha_1 - \alpha_2 \Big/ AR^2\right) - C_p$$

where p_{02} is the total pressure in the core region at the exit, the over bar indicate the mass averaged quantity, and α_1 and α_2 are the kinetic energy parameters at the inlet and exit of the diffuser.

For the case where the velocity profile at the inlet of diffuser is flat with a thin wall boundary layer, $\alpha_1 = 1$ However, due to the thickening of boundary layer through the

diffuser, α_2 is generally greater than unity. Nonetheless, it is often assumed that kinetic energy coefficient is equal to unity, then

$$K = C_{pi} - C_p$$

1.5.2.4 Ideal Pressure Recovery

Another parameter of interest is the ideal pressure recovery, C1, which is the pressure recovery coefficient assuming an inviscid flow through diffuser, which represent the maximum pressure recovery attainable by the given diffuser. When the definition of pressure recovery, the Bernoulli equation, and the conservation of mass and conservation of angular momentum principles are all employed, the following relationship is obtained for Cpi.

The design requirements for a good diffuser are as following-

1. Convey the flow efficiently transferring a portion of the kinetic energy into a static pressure rise.
2. It must accept a variety of inlet conditions including extreme swirl, blockage and Mach number.
3. Deliver the fluid with reasonable velocity and angle profiles without separated regions.
4. Wall curvature must not have a deleterious effect upon passage performance.
5. Pressure recovery achieved over a short axial length.

While obtaining the best possible design, some limitations are imposed on a diffuser:

1. Limited length
2. Specified area ratio
3. Specified cross- sectional shape
4. Maximum static pressure recovery
5. Minimum stagnation pressure loss

It is not hard to appreciate that the performance of the diffuser directly and often strongly influences the overall efficiency of the turbo machine. Thus the detailed processes which occur in diffusing elements must be carefully understood and thoroughly optimized if good turbo machinery performance is to be obtained.

Chapter 2

Literature Review

Flow through a diffuser is accompanied by reduction of mean kinetic energy and a consequent increase in pressure. It is more difficult to arrange for an efficient deceleration of flow than it is to obtain an efficient acceleration. There is a natural tendency in a diffusing process for the flow to break away from the walls of the diverging passage, reverse its direction, and flow back in direction of the pressure gradient. If the divergence is too rapid, this may result in the formation of eddies with consequent transfer of some kinetic energy into internal energy and a reduction in useful pressure rise. A small angle of divergence, however, implies a long diffuser and a high value of skin friction loss. Usually, flow separation in a diffuser is sought to be avoided due to the invoked additional pressure loss. Other than in many strongly separated flows, such as the flow over a backward facing step, the point of flow separation, in diffuser, is not defined by the geometry but entirely by the pressure gradient. Hence, diffuser flows are very sensitive and are difficult to predict with numerical means. Diffusers have been studied extensively in the past, since this is a very common flow configuration. Apart from the characterization of diffusers, these flows are used to study fundamental physics of pressure-driven flow separations.

Much of the extant data covering annular diffusers comes from the period from the 1950s through the 1980s. In this period of time, a considerable amount of research was done in the experimental laboratory to uncover some of the unusual performance characteristics of annular diffusers. By the late 1980s, however, the experimental research had reduced substantially due to a lack of government funding in a number of countries where the work had previously been extensive. It is, therefore, useful to review the data which has been made available and to look for patterns within this data. It is also necessary to determine how this data may best be used in future design studies and where it needs to be further improved. Much of the original data was taken in order to support studies of axial compressor discharge diffusion as flow leaves a compressor and enters a combustion chamber. Other work was done for exhaust diffusers of hydroelectric turbines, small gas turbines, and turbochargers. While these topics are still important today and there are important unresolved

questions, the level of activity has reduced. Now important research topics must be carefully selected for the more limited studies possible in future years.

Many persons have done a lot of tests on geometric parameter of diffuser Sovran and Klomp [1967] who tested over one hundred different geometries, nearly all of which had conically diverging centre bodies with an inlet radius ratio [Ri/Ro] of 0.55 to 0.70. The tests were carried out with a thin inlet boundary layer and the diffusers have free discharge. The tests were present as Contours of pressure recovery plotted against area ratio and non-dimensional length Howard et al [1967] also tested symmetrical annular diffusers with centre bodies of uniform diameter, using fully developed flow at inlet. The limits of the various flow regimes and the optimum performance lines were established. Besides it, some other researchers also contributed in the field of annular diffuser and concluded various important results. Much of the extent data covering the annular diffusers was done in the experimental laboratory to uncover some of the unusual performance characteristics of annular diffusers. But there are still some important unresolved questions. The reason for it is that the numbers of independent variables are large for annular diffusers. In the annular diffuser the flow take place between two boundary surfaces which can varies independently This chapter involves a systematic study of different geometric and flow parameters which influence the overall and internal performance of annular diffusers. In this regard the available literature has been examined with a view to make comments on the state of the art and to recognize the scope of further research on the subject.

2.1 Geometric and flow Parameters

The various parameters which influence the pressure recovery and the flow behaviour in a diffuser can be conveniently grouped as geometric and flow parameters .many flow situations require complicated geometrics where in either the central line or the wall are contoured. By suitable combination of wall angles, the diffusers can take variety of shapes, is characterized by the inclination of each wall to the axis.

The important geometric parameters are listed below.

- Area Ratio (Exit area/Entry Area)
- Aspect Ratio (entry depth/ entry width)
- Length to throat width ratio (Diffuser Length/Entry Width)
- Divergence Angle

The important flow parameters

- Inlet velocity profile
- Boundary layer thickness
- Blockage factors
- Turbulence parameters
- Inlet flow Reynolds numbers
- Degree of swirl at inlet

1.2 Effect of Geometric Parameters

In an annular diffuser, a number of different geometric variables can influence the variation of pressure recovery and inlet condition of flow. The basic equations of motion reveal the importance of both geometric and aerodynamic parameters on the ultimate performance of annular diffuser. The specification of a wide variety of geometric parameters is essential before the performance of diffuser is given. In this section, the various geometric parameters and there influence on diffuser performance is reviewed. Effect of geometry on the performance of annular diffuser governs by Arora B.B., Pathak B.D. [2005]. Numerical analysis of the impact of conical diffuser geometry change on velocity distribution in its outlet cross-section by Krystyna prync-skotniczny [2006]. Correlation of annular diffuser performance with geometry, swirl and blockage is given by Japikse Dr. David [2003]**.**

2.2.1 Passage Divergence and Length

Area ratio and non-dimension length prescribes the overall diffusion and pressure–gradient respectively, which is the principle factor in boundary layer development. The study by Henry and Wood [1958] is useful to understand the subsonic annular diffuser. Two diffusers with area ratio 2.1 and divergence of 5º and 10º were tested at various Mach number. It found by this study that most of data clusters around a line of constant Effectiveness. It is also observed that the inner wall is being starved of fluid. If a higher divergence had been used, then one might anticipate stall on the inner surface. An extensive study is carried out by Kmonicek and Hibs [1974] in which, the pressure loss coefficient is found out on the basis of the work of

compression required to meet the static pressure rise, the results are very interesting but difficult to understand due to use of unconventional terminology

Sovran and Klomp [1967] and Howard et al. [1967] produced the first widely used annular diffuser maps for channel diffusers. Sovran and Klomp conducted a large number of performance measurements which spanned a broad selection of geometric types of diffusers. The map is only a broad representation of the bulk of configurations tested in the vicinity of their best performance areas. The poorer diffusers are not well defined by the map. These maps also show optimal diffuser geometrics under different conditions and two optimum lines are established. The same results were found out by Howard et al [1967]. The important difference between this and the Sovran and Klomp [1967] map was that the latter was made for very low inlet aerodynamic blockage whereas the former study was carried out for fully developed inlet profiles, implying high aerodynamic blockage Along the line of peak recovery there is fairly good agreement between the two maps but in the region of heavy transitory stall the maps disagree substantially.

Johnston [1959] and Johnston [1953] reported a study of four different annular diffusers. Three of the four agree tolerably well with the basics Sovran and Klomp [1967] map, one of them disagree substantially; the case a strong disagreement is probably in stall. Srinath [1968] studied four equiangular annular diffuser with $2\theta =$ 7º, 10º, 15º and 20º respectively. Tests were reported with a variety of L/Δr values. An extensive study of diffusers which, although annular, begin with a circular cross section was reported by Ishikawa and Nakamura [1989]. The author found that the performance of the diffuser differed significantly depending on whether it is parallel or diverging for L/r1 greater than about 2. When both types have the same non dimensional length and area ratio, the parallel diffuser has the higher CP. The lines of optimum performance are also drawn. Ishikawa and Nakamura [1989], also attempted to compare their results with those of Sovran and Klomp[1967], for a conventional annular diffuser for the same wall length and area ratio, their diffuser was superior, but since the inlet conditions were different in the two studies, this conclusion is only tentative. It was also found that the addition of a conical centre body improves the performance of simple conical diffusers with appreciable or large stall. The study carried out by Moller [1965], who designed an axial to radial band with the intention of eliminating diffusion in the inlet region; found that the peak pressure recovery for the entire band and radial diffuser sections was 0.88 and 0.82 for the low blockage

and high blockage cases, respectively. Cockrell and Markland [1963], reported that a variation in the area ratio from 2.5 to 8.0 has a small effect on the loss coefficients of conical diffusers.

2.2.2 Wall Contouring

Several annular diffuser studies have been published in which contoured walls were an essential part of the design problem. Thayer [1971], reported that curved wall diffusers had pressure recovery as high as 0.61 to 0.65 for an area ratio of 2.15. An extensive study by Stevens and Williams [1980], reported that for curved wall diffuser, good pressure recovery was found for a loss significantly below the level which would be expected from pressure recovery loss correlation , but pressure recovery values were lower then those which would be expected from the Sovran and Klomp [1967], map. Upon careful examination, it was determined that the boundary layers in this diffuser are different from those which would be expected in most diffuser studies. Takehira et al [1977], presented extensive data for a large set of both straight annular diffusers and curved wall diffusers, and determined that the use of strong curvature at the exit of diffuser was not debilitating but did produce a penalty compared to no curved diffusers or diffusers with curvature at the inlet.

An additional study by Japikse [2000] shows that wall contouring is an important parameter regarding pressure recovery. Adkins et al [1983], tested an annular diffuser of constant outer radius and a conical centre body with cones of different angles. In general the pressure recovery increases with decreasing cone angle for various area ratios, but the 132º and sometimes the 45º-cone angle produced lower pressure recoveries than an equivalent sudden expansion. This was attributed to a large and rapid separation at the base of the cone where the diffuser starts. Adding a radius to the base of the cone so that it smoothly blended into the upstream hub, was found to improve the performance.

2.3 Effects of Flow Parameters

2.3.1 Aerodynamic Blockage

The basic boundary layer equations reveal the importance of the displacement thickness as a characteristic length scale of the inlet boundary layer flow .Startford and Tubbs [1965] and (evidently) Bragg recognized the importance of the boundary

layer displacement thickness to pressure recovery process .it is clear that thin inlet boundary layer should be beneficial to high diffuser recovery and that longer diffusers are necessary to achieve high level of recovery as the inlet boundary thickness increases. Thayer [1971], reported that curved wall diffusers had pressure recovery as high as 0.61 to 0.65 for an area ratio of 2.15. An extensive study by Stevens and Williams [1980], reported that for curved wall diffuser, good pressure recovery was found for a loss significantly below the level which would be expected from pressure recovery loss correlation , but pressure recovery values were lower then those which would be expected from the Sovran and Klomp [1967],map. Klein [1995] compared Stevens and Williams [1980] data with the result of Sovern and Klomp[1967] for an inlet blockage of .02 and with predictions using the latter's method for diffuser performance fat larger blockages. A comprehensive study on the influence of aerodynamic blockage on annular diffuser performance cariedout by Globel and Japikse [1981].similar measurements were made at 20º and 40º of inlet swirl. In all cases the data trend was in the direction of reduced pressure recovery for increased aerodynamic blockage. Upon careful examination, it was determined that the boundary layers in this diffuser are different.Mazumdar P.M. et,al   [2003] done aerodynamic design optimization at cased. . First, the influence of inlet conditions
On annular diffuser performance is more complicated than for channel and conical diffuser. In this case, both the hub and casing surfaces can develop boundary layers with significantly different histories. The two differing boundary layers will experience different growth processes as they pass through the diffuser. Furthermore, blockage on one wall has the effect of modifying the effective flow area and hence the core flow velocity, thereby influencing the growth of the boundary layer on the opposite wall. Hence complex interactions can develop within the diffuser.

2.3.2 Inlet Swirl

The method of swirl generation can itself influence the performance of an annular diffuser and, therefore, consideration must be given first to this question. Most investigators have chosen to generate swirled in a radial inflow plane in order to take advantage of the simple cascade design geometry. Others have preferred to use axial cascade which have the advantage that they more closely simulate specific turbo machinery flow condition and permit control of the spacing between the diffuser and the vanes in form that may be more typical of an actual turbo machine. On the other

hand axial cascade invariably introduces tip and hub leakage since the cascades are of a variable geometry type, an effective sealing is impossible. In addition to inlet swirl, there may be changes in inlet turbulence intensity, velocity or total pressure gradients, vorticity or wake shading, and inlet aerodynamic blockage may change indirectly as a function of the swirl angle as it is varied. In order for firm conclusion to be drawn, the effect of swirl variation must be deciphered from the performance data Divehi and Kartavenko [1975] also reported by the same type of study that the best performance can be achieved between the ranges of 10º to 20º of inlet swirl angle. A study is presented by Japikse and Pamprreen [1979] of an exhaust diffuser and hood found that substantial recovery has been achieved even up to swirl angle in excess of 40º. Steenbergen W. J. Voskamp [1998] The rate of decay of swirl in turbulent pipe flow He found that on increase of swirl number the rate of increase.Guo Bayou et,al [2001]done the CFD simulation of precession in sudden pipe expansion flows with low inlet swirl. It seems that higher swirl level require fine grid. Numerical Investigation of Swirling Flow in Annular Diffusers With a Rotating Hub Installed at the Exit of Hydraulic Machines is done by Kochevsky A.N. [2000] Numerical investigation of swirl flow on conical diffuser was done by the Walter Gyllenram et, al [2004] . Najafi A.F. [2005] have done Numerical analysis of turbulent swirling decay pipe flow The flow characteristics through a rotating honeycomb and resulting downstream swirling decay flow through a fixed pipe have been investigated in this research. The modelling of the rotating honeycomb is observed to be of major importance for the prediction of the downstream flow. Several methods are used and tested. The flow field properties obtained by the honeycomb tubes which are the annular cylinders in our axi-symmetric computations have a considerable effect on the downstream flow. Ogor Buntiæ et al, [2006]give the An Adaptive Turbulence Model for Swirling Flow .

2.3.3 Inlet Turbulence

With long approach pipes diffuser performance rises as approach length increases. This was first noted in the Cockrell and Markland [1963] and attributed this to changes in turbulence which enhances mixing transverse to flow directions, thus reducing the distortions. Indeed, the core turbulence intensity of developing pipe flow rises significantly from La /D is equal to 20 to 45 and than remains nearly constant.

Two studies have been published which considered variation in inlet turbulence intensity or structure for there impact on annular diffuser performance. The data of Coladieiepro et al [1974] have included both low and high inlet turbulence intensity levels, and this may be explanation for the unusual measurements observed at different blockage. The second study is the work of Williams and Stevens [1969] and Stevens and Fry (1973), which showed that substantial improvements in radial momentum transport were achieved by turbulence producing grids and wall spoilers. Additional results by Hestermann et al [1995], and Klein [1995] also show that increasing the level of turbulence to 6 – 8.5 % is beneficial in increasing the pressure recovery and, in one case of removing the separation of stalled diffuser. Ubertini and Desideri [2000] determined the flow development in terms of the mean and fluctuating components of the velocity and turbulence dissipating eddy length scales in annular exhaust diffuser.The K-ε and other turbulent models are evaluated with respect to their applicability in swirling flows by Arora.B.B. et.al[2005] In most of the past numerical simulations, swirling air is introduced around this, in most cases perpendicular to the axis. In this configuration, it is straightforward to specify the inlet velocity profiles Ogor Buntiæ et al, [2006]give the An Adaptive Turbulence Model for Swirling Flow . Leschziner M.A.[2004] had hdone modelling turbulent separated flow in the context of aerodynamic applications. Bajcar Tom et, al [2006] Heat transfer influenced by turbulent airflow inside an axially rotating diffuser. Tornblom Olle[2006] give an Experimental and computational studies of turbulent separating internal flows The experimental investigation of the mean flow and turbulence properties revealed a flow with several interesting characteristics: strong and suddenly imposed shearing, non-equilibrium turbulence, separation, reattachment and turbulence relaxation. The conclusion of above study is that the effect of increasing inlet turbulence intensity is to increase pressure recovery.

2.3.4 Mach number Influence

Most annular diffuser research has been carried out at low inlet mach numbers. However, several studies have shown measurement at different Mach number. The study by Thayer [1971], Wood and Henry [1958] and Japikse and Pampreen [1979] illustrate virtual independence of recovery with Mach number up to some critical level of approximately 0.80 to 1.1. The actual level depends on method of

measurement and the type of inlet. Wood and Henry [1971] show that a shock structure must be presented before the performance begins to deteriorate, but the reference Mach number may have little to do with the actual shock location and shock structure. In most cases, the reduction of performance with Mach number is very slight but in a few cases there can be a degradation of five or ten point of performance recovery.

2.3.5 Reynolds Number Influence

Viscosity is an important parameter in any fluid dynamic process and normally appears in the form of a Reynolds number. Typically, diffusers are characterized by a Reynolds number based on an inlet hydraulic diameter. All studies reported that the Reynolds number is a comparatively weak parameter as long as the flow is in the fully turbulent regime. Crockrell and Markland [1963] state that a variation of the inlet Reynolds number has no significant effect on the diffuser performance if this variation is uncoupled from its effects on the inlet boundary layer parameters. For Reynolds number variation within the range of 2×10^4–7×10^5, they also pointed out that the diffuser performance would be practically independent of Reynolds number provided the inlet boundary parameters remain constant. Sharan [1972] reported that for thick boundary layers, there is no change in pressure recovery as the Reynolds number increases.

2.3.6 Boundary Layer Parameter

The flow in diffuser is governed by the behaviour of the boundary layers at the diffuser walls. The deceleration of the flow through the diffuser produces a pressure rise in the stream wise direction. The wall shear layers are therefore subjected to a positive or adverse pressure gradient. As is well known, an adverse pressure gradients cause the wall boundary layers to thicken and possibly separate from the diffuser walls, forming areas of backflow in the diffuser. The net result of thinking of the wall boundary layers or the formation of regions of backflow is the blockage of flow area which reduces the effective area available to the flow. Reduction in effective flow area in turn results in a reduced pressure rise through the diffuser.

2.3.7 Boundary Layer Suction

The effect of suction consists in the removal of decelerated fluid particles from the boundary layer before they are given a chance to cause separation. Wilbur and Higginbotham [1957] investigated the suction phenomenon and found that a suction flow rate of 2.3% increased the static pressure rise by 25 – 60% and decreased the measured total pressure loss by 63%. In another study by Wilbur and Higginbotham [1955], it is shown that suction control is not efficient when applied in an extensive backflow region such as exists immediately downstream of an abruptly turned body. Experiments by Juhasz [1974], on short annular diffuser showed that the diffuser exit profiles could be shifted either towards the hub or towards the casing of annulus by bleeding off a small fraction of the flow through the inner and outer wall respectively. Boundary Layer Suction is also adopted by Ackert [1967], for both channel and conical diffuser with large divergence angle.

2.3.8 Blowing and Injection

Wilbur and Higginbotham [1955], found that at an injection rate of 3.4%, a 33% increases in the measured static pressure rise and a 50% decrease in the measured total pressure loss can be obtained. Juhasz [1974], have reported results of their investigations on the effect of injecting secondary fluid into wild angle conical diffusers through annular slot at inlet. Injection was found to result in considerable improvement in the uniformity of exit flow as well as in the magnitude of pressure recovery.

Chapter 3

CFD ANALYSIS

FLUENT is a state-of-the-art computer program for modeling fluid flow and heat transfer in complex geometries. FLUENT provides complete mesh flexibility, solving your flow problems with unstructured meshes that can be generated about complex geometries with relative ease. Supported mesh types include 2D triangular/quadrilateral, 3D tetrahedral/hexahedral/pyramid/wedge, and mixed (hybrid) meshes. FLUENT also refine or coarsen grid based on the flow solution.

3.1 Program Capabilities

The FLUENT solver has the following modeling capabilities:

- 2D planar, 2D axisymmetric, 2D axisymmetric with swirl (rotationally symmetric), and 3D flows
- Quadrilateral, triangular, hexahedral (brick), tetrahedral, prism (wedge), pyramid, and mixed element meshes
- Steady-state or transient flows
- Incompressible or compressible flows, including all speed regimes (low subsonic, transonic, supersonic, and hypersonic flows)
- Inviscid, laminar, and turbulent flows
- Newtonian or non-Newtonian flows
- Heat transfer, including forced, natural, and mixed convection, conjugate (solid/fluid) heat transfer, and radiation
- Lumped parameter models for fans, pumps, radiators, and heat exchangers
- Inertial (stationary) or non-inertial (rotating or accelerating) reference frames
- Multiple reference frame (MRF) and sliding mesh options for modeling multiple moving frames
- Mixing-plane model for modeling rotor-stator interactions, torque converters, and similar turbomachinery applications with options for mass conservation

3.2 Planning CFD Analysis

The following consideration should be taken while planning CFD analysis:

3.2.1 Definition of the Modeling Goals

What specific results are required from the CFD model and how will they be used? What degree of accuracy is required from the model?

3.2.2 Choice of the Computational Model

How will you isolate a piece of the complete physical system to be modeled? Where will the computational domain begin and end? What boundary conditions will be used at the boundaries of the model? Can the problem be modeled in two dimensions or is a three-dimensional model required? What type of grid topology is best suited for this problem?

3.2.3 Choice of Physical Models

Is the flow inviscid, laminar, or turbulent? Is the flow unsteady or steady? Is heat transfer important? Will you treat the fluid as incompressible or compressible? Are there other physical models that should be applied?

3.2.4 Determination of the Solution Procedure

Can the problem be solved simply, using the default solver formulation and solution parameters? Can convergence be accelerated with a more judicious solution procedure? Will the problem fit within the memory constraints of your computer, including the use of multigrid? How long will the problem take to converge on your computer?

Careful consideration of these issues before beginning CFD analysis will contribute significantly to the success of modeling effort.

Problem Solving Steps

Once the important features of the problem are determined, the basic procedural steps are as follows:

- Create the model geometry and grid.
- Start the appropriate solver for 2D or 3D modeling.
- Import the grid.
- Check the grid.
- Select the solver formulation.
- Choose the basic equations to be solved: laminar or turbulent (or inviscid), chemical species or reaction, heat transfer models, etc. Identify additional

models needed: fans, heat exchangers, porous media, etc.

- Specify material properties.
- Specify the boundary conditions.
- Adjust the solution control parameters.
- Initialize the flow field.
- Calculate a solution.
- Examine the results.
- Save the results.
- If necessary, refine the grid or consider revisions to the numerical or physical model.

3.3 Linearization: Implicit vs. Explicit

In both the segregated and coupled solution methods the discrete, non-linear governing equations are linearized to produce a system of equations for the dependent variables in every computational cell. The resultant linear system is then solved to yield an updated flow-field solution.

The manner in which the governing equations are linearized may take an "implicit" or "explicit" form with respect to the dependent variable (or set of variables) of interest. By implicit or explicit we mean the following:

Implicit: For a given variable, the unknown value in each cell is computed using a relation that includes both existing and unknown values from neighboring cells. Therefore each unknown will appear in more than one equation in the system, and these equations must be solved simultaneously to give the unknown quantities.

Explicit: For a given variable, the unknown value in each cell is computed using a relation that includes only existing values. Therefore each unknown will appear in only one equation in the system and the equations for the unknown value in each cell can be solved one at a time to give the unknown quantities.

3.4 Discretization

The governing equations are converted into algebraic equations with the help of the

finite volume technique that can be solved numerically. This control volume technique consists of integrating the governing equations about each control volume, yielding discrete equations that conserve each quantity on a control-volume basis. Discretization of the governing equations can be illustrated most easily by considering the steady-state conservation equation for transport of a scalar quantity φ. This is demonstrated by the following equation written in integral form for an arbitrary control volume V as follows:

$$\oint \rho \phi \vec{v} \cdot d\vec{A} = \oint \Gamma_\phi \nabla \phi \cdot d\vec{A} + \int_V S_\phi \, dV$$

where

ρ   = density

v   = velocity vector A = surface area vector

Γ_φ = diffusion coefficient for φ

∇_φ = gradient of φ

S_φ = source of φ per unit volume

Above equation is applied to each control volume, or cell, in the computational domain. Discretization of Equation on a given cell yields

$$\sum_f^{N_{faces}} \rho_f \vec{v}_f \phi_f \cdot \vec{A}_f = \sum_f^{N_{faces}} \Gamma_\phi (\nabla \phi)_n \cdot \vec{A}_f + S_\phi V$$

Where

N_{faces}	=	number of faces enclosing cell
φf	=	value of φ convected through face f
$\rho_f \, v_f \, A_f$	=	mass flux through the face
A_f	=	area of face f, |A
$(\nabla \varphi)_n$	=	magnitude of ∇φ normal to face f
V	=	cell volume

The equations take the same general form as the one given above and apply readily to multi-dimensional, unstructured meshes composed of arbitrary polyhedral, the

discrete values of the scalar φ at the cell centers. However, face values φ_f is required for the convection terms in Equation and must be interpolated from the cell center values. This is accomplished using an upwind scheme.

Up winding means that the face value φf is derived from quantities in the cell upstream, or "upwind," relative to the direction of the normal velocity v_n

3.5 Under relaxation

In the iterative solution of the algebric or in the overall iterative scheme employed for handling nonlinearity, it is often desirable to speed up the changes, from iteration to iteration, in the values of dependent variables. This process is called under relaxation. It is a powerful device to avoid divergence in the iterative solution of strongly non linear problems. If unstable or divergent behavior is observed for a particular value of relaxation factors reduce the value of the factors for better convergence of the solution.

3.6 Convergence criteria

Finally, one needs to set the convergence criteria for the iterative method. Usually, there are two levels of iterations, within which the linear equations are solved and outer iteration that deal with the non-linearity and coupling of the equations. Deciding when to stop the iterative process on each level is important, from both the efficiency and accuracy point of view. A numerical is said to be convergent if the solution of the discretized equations tend to exact the solution of the differential as the grid spacing tends to be zero. For convergence criteria around 10^{-6} for X velocity variable, the results are stable in the present problem.

3.7 Implementation of boundary conditions

Each CV provides one algebric equation. Volume integrals are calculated for every control volume, but flux through Cv faces coinciding with the domain boundary requires special treatment. These boundary fluxes must be known, or be expressed as a combination of interior values and boundary data. Two types of boundary conditions need to be specified.

Dirchlet conditions where variable values are given at boundary nodes.

Neuman conditions where the boundary fluxes are incorporated at the boundary.

3.7.1 Inlet boundary condition

The present analysis involves the velocity with and without swirl. The incorporation of velocity without swirl can be specified by any one of the velocity specification methods described in FLUENT. Turbulence intensity is specified as

$$I = 0.16(Re_{DH})^{-1/8} \times 100$$

The inlet based on the Reynolds number with respect to equivalent flow diameter.

Where, Re_{DH} is the Reynolds number based on the hydraulic diameter.

For specifying the velocity in case of flow with swirl, tangential component of velocity will also have to be defined along with axial component. Velocity components are calculated on the basis of inlet swirl angle. In the present case swirl angle of 5, 10, 15, 20, 25 degrees are considered. Inlet velocity of 50 m/s with flat profile is considered for both the cases.

3.7.2 Outlet boundary condition

Atmospheric pressure condition is applied at the outlet boundary condition and set a "back flow" conditions is also specified if the flow reverses direction at the pressure outlet boundary during the solution process. In the "back flow" condition turbulence intensity is specified based on the equivalent flow diameter.

3.7.3 Wall boundary condition

Wall boundary conditions are used to bind fluid and solid regions. In viscous flows the no slip boundary condition is enforced at the walls. Wall roughness affects the drag (resistance) and heat and mass transfer on the walls. Hence roughness effects were considered for the present analysis and a specified roughness based on law of wall modified for roughness is considered. Two inputs to be specified are the physical roughness height and the roughness constant. And the default roughness constant (0.5) is assigned which indicates the uniform sand grain roughness.

3.7.4 Axis boundary condition

The present analysis is modeled with axisymmetric geometry. Hence the centre line of geometry is specified as the axis boundary condition.

Chapter 4

DATA OBTAINED FROM CFD ANALYSIS

In the straight core annular diffuser for various swirl angle data are (at section x=0.1)

Y/Ym	U/Um	S
0	0	0
0	3.00E-05	0
0.00248	0.42806	0
0.00499	0.47973	0
0.00752	0.49544	0
0.01008	0.5066	0
0.01266	0.51602	0
0.01526	0.52459	0
0.0179	0.53272	0
0.02056	0.5406	0
0.02325	0.5484	0
0.02596	0.55591	0
0.03829	0.58692	0
0.04117	0.59428	0
0.05637	0.63101	0
0.06516	0.64881	0
0.07157	0.66199	0
0.08678	0.6877	0
0.09203	0.69503	0
0.10198	0.70908	0
0.11718	0.72742	0
0.11889	0.72923	0

0.13239	0.74362	0
0.14574	0.75667	0
0.14759	0.75849	0
0.16279	0.77244	0
0.17259	0.78106	0
0.178	0.78586	0
0.1932	0.79892	0
0.19942	0.80415	0
0.2084	0.81175	0
0.22361	0.82446	0
0.22625	0.82663	0
0.23881	0.83702	0
0.25306	0.84872	0
0.25402	0.8495	0
0.26922	0.86182	0
0.27988	0.87032	0
0.28442	0.87397	0
0.29963	0.88588	0
0.30667	0.89124	0
0.31483	0.89748	0
0.33003	0.90871	0
0.33347	0.91112	0
0.34524	0.91947	0
0.36025	0.9296	0
0.36044	0.92973	0
0.37564	0.93938	0

0.38703	0.94613	0
0.39085	0.94838	0
0.40605	0.95661	0
0.41379	0.96045	0
0.42125	0.96411	0
0.43646	0.97086	0
0.44055	0.97248	0
0.45166	0.97746	0
0.46687	0.98347	0
0.4673	0.98362	0
0.48763	0.98948	0
0.49831	0.99195	0
0.50856	0.99427	0
0.52933	0.99763	0
0.52949	0.99765	0
0.55041	0.99952	0
0.56039	0.99983	0
0.57134	1	0
0.59146	0.99934	0
0.59227	0.9993	0
0.6132	0.99755	0
0.62256	0.99644	0
0.63413	0.99488	0
0.65369	0.99167	0
0.65505	0.99142	0
0.67598	0.98712	0
0.68484	0.98499	0

0.69691	0.98188	0
0.71601	0.97607	0
0.71784	0.97549	0
0.73877	0.96771	0
0.74721	0.96408	0
0.7597	0.95848	0
0.77843	0.9489	0
0.78063	0.94774	0
0.80155	0.93555	0
0.80968	0.93034	0
0.82248	0.92198	0
0.84095	0.90884	0
0.84341	0.90708	0
0.86434	0.89102	0
0.87224	0.88451	0
0.88527	0.87379	0
0.90356	0.85751	0
0.90619	0.85518	0
0.92712	0.83452	0
0.93491	0.82475	0
0.94805	0.8084	0
0.96627	0.77477	0
0.96898	0.76981	0
0.97222	0.76103	0
0.97543	0.74978	0
0.97861	0.73662	0
0.98176	0.72082	0

0.98487	0.70146	0
0.98796	0.67704	0
0.99102	0.64446	0
0.99404	0.5943	0
0.99703	0.50213	0
1	0	0
0	0	7.5
0	0.00003	7.5
0.00248	0.44984	7.5
0.00499	0.50435	7.5
0.00752	0.5224	7.5
0.01008	0.53533	7.5
0.01266	0.54645	7.5
0.01526	0.55677	7.5
0.0179	0.56671	7.5
0.02056	0.57648	7.5
0.02325	0.58625	7.5
0.02596	0.59565	7.5
0.03829	0.63387	7.5
0.04117	0.64297	7.5
0.05637	0.68561	7.5
0.06516	0.70428	7.5
0.07157	0.71814	7.5
0.08678	0.74239	7.5
0.09203	0.74871	7.5
0.10198	0.76084	7.5
0.11718	0.77584	7.5

0.11889	0.77728	7.5
0.13239	0.78877	7.5
0.14574	0.79917	7.5
0.14759	0.80062	7.5
0.16279	0.81182	7.5
0.17259	0.81881	7.5
0.178	0.82272	7.5
0.1932	0.83342	7.5
0.19942	0.83772	7.5
0.2084	0.844	7.5
0.22361	0.85446	7.5
0.22625	0.85623	7.5
0.23881	0.86476	7.5
0.25306	0.87422	7.5
0.25402	0.87486	7.5
0.26922	0.88465	7.5
0.27988	0.89125	7.5
0.28442	0.89409	7.5
0.29963	0.90311	7.5
0.30667	0.90705	7.5
0.31483	0.91166	7.5
0.33003	0.91972	7.5
0.33347	0.92141	7.5
0.34524	0.92728	7.5
0.36025	0.93426	7.5
0.36044	0.93435	7.5
0.37564	0.94091	7.5

0.38703	0.94546	7.5
0.39085	0.94697	7.5
0.40605	0.95246	7.5
0.41379	0.95503	7.5
0.42125	0.95748	7.5
0.43646	0.96208	7.5
0.44055	0.96323	7.5
0.45166	0.96681	7.5
0.46687	0.97137	7.5
0.4673	0.97149	7.5
0.48763	0.9763	7.5
0.49831	0.97863	7.5
0.50856	0.98088	7.5
0.52933	0.98502	7.5
0.52949	0.98505	7.5
0.55041	0.98867	7.5
0.56039	0.99023	7.5
0.57134	0.99181	7.5
0.59146	0.99439	7.5
0.59227	0.99448	7.5
0.6132	0.9966	7.5
0.62256	0.99742	7.5
0.63413	0.99826	7.5
0.65369	0.99938	7.5
0.65505	0.99944	7.5
0.67598	0.99999	7.5
0.68484	1	7.5

0.69691	0.99979	7.5
0.71601	0.99874	7.5
0.71784	0.9986	7.5
0.73877	0.99607	7.5
0.74721	0.99451	7.5
0.7597	0.99195	7.5
0.77843	0.98667	7.5
0.78063	0.98601	7.5
0.80155	0.9782	7.5
0.80968	0.97455	7.5
0.82248	0.9686	7.5
0.84095	0.95869	7.5
0.84341	0.95735	7.5
0.86434	0.94474	7.5
0.87224	0.9395	7.5
0.88527	0.93087	7.5
0.90356	0.91751	7.5
0.90619	0.9156	7.5
0.92712	0.89833	7.5
0.93491	0.88977	7.5
0.94805	0.87544	7.5
0.96627	0.84352	7.5
0.96898	0.83882	7.5
0.97222	0.82974	7.5
0.97543	0.81753	7.5
0.97861	0.80284	7.5
0.98176	0.78483	7.5

0.98487	0.76258	7.5
0.98796	0.73468	7.5
0.99102	0.69803	7.5
0.99404	0.64299	7.5
0.99703	0.54551	7.5
1	0	7.5
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0	0.00003	12
0.00248	0.4346	12
0.00499	0.48822	12
0.00752	0.50634	12
0.01008	0.51903	12
0.01266	0.52981	12
0.01526	0.53977	12
0.0179	0.54933	12
0.02056	0.55871	12
0.02325	0.5681	12
0.02596	0.57716	12
0.03829	0.61445	12
0.04117	0.6233	12
0.05637	0.66582	12
0.06516	0.68504	12
0.07157	0.69928	12
0.08678	0.72489	12
0.09203	0.73167	12
0.10198	0.74467	12
0.11718	0.76073	12

0.11889	0.76226	12
0.13239	0.77444	12
0.14574	0.78527	12
0.14759	0.78679	12
0.16279	0.79823	12
0.17259	0.80523	12
0.178	0.80915	12
0.1932	0.8197	12
0.19942	0.82388	12
0.2084	0.82999	12
0.22361	0.84008	12
0.22625	0.84177	12
0.23881	0.84994	12
0.25306	0.859	12
0.25402	0.85961	12
0.26922	0.86901	12
0.27988	0.8754	12
0.28442	0.87815	12
0.29963	0.88696	12
0.30667	0.89086	12
0.31483	0.89541	12
0.33003	0.90348	12
0.33347	0.9052	12
0.34524	0.91114	12
0.36025	0.91828	12
0.36044	0.91837	12
0.37564	0.92514	12

0.38703	0.92987	12
0.39085	0.93143	12
0.40605	0.9372	12
0.41379	0.93994	12
0.42125	0.94253	12
0.43646	0.94749	12
0.44055	0.94875	12
0.45166	0.95265	12
0.46687	0.95773	12
0.4673	0.95787	12
0.48763	0.9634	12
0.49831	0.96617	12
0.50856	0.96889	12
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0.52949	0.97416	12
0.55041	0.97896	12
0.56039	0.98113	12
0.57134	0.98338	12
0.59146	0.98724	12
0.59227	0.98738	12
0.6132	0.99086	12
0.62256	0.99229	12
0.63413	0.99388	12
0.65369	0.99626	12
0.65505	0.9964	12
0.67598	0.9983	12
0.68484	0.99893	12

0.69691	0.99954	12
0.71601	0.99999	12
0.71784	1	12
0.73877	0.99945	12
0.74721	0.99889	12
0.7597	0.9978	12
0.77843	0.99523	12
0.78063	0.99489	12
0.80155	0.99066	12
0.80968	0.98856	12
0.82248	0.98509	12
0.84095	0.979	12
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0.87224	0.96623	12
0.88527	0.96012	12
0.90356	0.94959	12
0.90619	0.94808	12
0.92712	0.93252	12
0.93491	0.92405	12
0.94805	0.90988	12
0.96627	0.87687	12
0.96898	0.87199	12
0.97222	0.86287	12
0.97543	0.85119	12
0.97861	0.83755	12
0.98176	0.82109	12

0.98487	0.80076	12
0.98796	0.77479	12
0.99102	0.73964	12
0.99404	0.68498	12
0.99703	0.58567	12
1	0	12
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0	0.00002	17
0.00248	0.38698	17
0.00499	0.43285	17
0.00752	0.44626	17
0.01008	0.45639	17
0.01266	0.46528	17
0.01526	0.47362	17
0.0179	0.48174	17
0.02056	0.4898	17
0.02325	0.49799	17
0.02596	0.5061	17
0.03829	0.54199	17
0.04117	0.55048	17
0.05637	0.59651	17
0.06516	0.62015	17
0.07157	0.63764	17
0.08678	0.67194	17
0.09203	0.6813	17
0.10198	0.69926	17
0.11718	0.72094	17

0.11889	0.7229	17
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0.14574	0.75165	17
0.14759	0.75348	17
0.16279	0.76674	17
0.17259	0.77461	17
0.178	0.779	17
0.1932	0.79059	17
0.19942	0.79514	17
0.2084	0.80176	17
0.22361	0.81263	17
0.22625	0.81446	17
0.23881	0.82323	17
0.25306	0.83296	17
0.25402	0.83361	17
0.26922	0.8437	17
0.27988	0.85058	17
0.28442	0.85354	17
0.29963	0.86308	17
0.30667	0.86734	17
0.31483	0.87231	17
0.33003	0.88123	17
0.33347	0.88316	17
0.34524	0.88983	17
0.36025	0.89803	17
0.36044	0.89814	17
0.37564	0.90607	17

0.38703	0.91175	17
0.39085	0.91364	17
0.40605	0.92071	17
0.41379	0.92412	17
0.42125	0.92736	17
0.43646	0.93357	17
0.44055	0.93515	17
0.45166	0.93995	17
0.46687	0.94617	17
0.4673	0.94634	17
0.48763	0.95308	17
0.49831	0.95642	17
0.50856	0.95972	17
0.52933	0.96602	17
0.52949	0.96606	17
0.55041	0.97184	17
0.56039	0.97447	17
0.57134	0.97723	17
0.59146	0.98203	17
0.59227	0.98222	17
0.6132	0.98668	17
0.62256	0.98854	17
0.63413	0.99064	17
0.65369	0.99384	17
0.65505	0.99403	17
0.67598	0.99671	17
0.68484	0.99764	17

0.69691	0.99867	17
0.71601	0.99975	17
0.71784	0.99982	17
0.73877	1	17
0.74721	0.99975	17
0.7597	0.99913	17
0.77843	0.99731	17
0.78063	0.99705	17
0.80155	0.99365	17
0.80968	0.99186	17
0.82248	0.98888	17
0.84095	0.98342	17
0.84341	0.98268	17
0.86434	0.97512	17
0.87224	0.97169	17
0.88527	0.96604	17
0.90356	0.95634	17
0.90619	0.95496	17
0.92712	0.94089	17
0.93491	0.93326	17
0.94805	0.92051	17
0.96627	0.88966	17
0.96898	0.88511	17
0.97222	0.87626	17
0.97543	0.86465	17
0.97861	0.85088	17
0.98176	0.83405	17

0.98487	0.81312	17
0.98796	0.7864	17
0.99102	0.75047	17
0.99404	0.69526	17
0.99703	0.59578	17
1	0	17
0	0	25
0	0.00002	25
0.00248	0.35385	25
0.00499	0.39651	25
0.00752	0.40828	25
0.01008	0.41791	25
0.01266	0.42667	25
0.01526	0.43507	25
0.0179	0.44334	25
0.02056	0.45161	25
0.02325	0.46001	25
0.02596	0.46832	25
0.03829	0.50476	25
0.04117	0.51341	25
0.05637	0.55917	25
0.06516	0.58195	25
0.07157	0.59887	25
0.08678	0.63118	25
0.09203	0.63988	25
0.10198	0.65658	25
0.11718	0.67687	25

0.11889	0.67876	25
0.13239	0.69375	25
0.14574	0.70684	25
0.14759	0.70866	25
0.16279	0.72243	25
0.17259	0.73095	25
0.178	0.73568	25
0.1932	0.74868	25
0.19942	0.75397	25
0.2084	0.76163	25
0.22361	0.77459	25
0.22625	0.77683	25
0.23881	0.78752	25
0.25306	0.7996	25
0.25402	0.80041	25
0.26922	0.81312	25
0.27988	0.82185	25
0.28442	0.82559	25
0.29963	0.83767	25
0.30667	0.84304	25
0.31483	0.84928	25
0.33003	0.86035	25
0.33347	0.86269	25
0.34524	0.8708	25
0.36025	0.88054	25
0.36044	0.88066	25
0.37564	0.88991	25

0.38703	0.89645	25
0.39085	0.89862	25
0.40605	0.90674	25
0.41379	0.91067	25
0.42125	0.91438	25
0.43646	0.92157	25
0.44055	0.92341	25
0.45166	0.92893	25
0.46687	0.9361	25
0.4673	0.9363	25
0.48763	0.94413	25
0.49831	0.94801	25
0.50856	0.95187	25
0.52933	0.95924	25
0.52949	0.95929	25
0.55041	0.96598	25
0.56039	0.969	25
0.57134	0.97219	25
0.59146	0.97771	25
0.59227	0.97792	25
0.6132	0.98306	25
0.62256	0.98522	25
0.63413	0.98768	25
0.65369	0.99151	25
0.65505	0.99175	25
0.67598	0.9951	25
0.68484	0.99631	25

0.69691	0.9977	25
0.71601	0.99929	25
0.71784	0.9994	25
0.73877	1	25
0.74721	0.99986	25
0.7597	0.99938	25
0.77843	0.99764	25
0.78063	0.99739	25
0.80155	0.99396	25
0.80968	0.99212	25
0.82248	0.98905	25
0.84095	0.98339	25
0.84341	0.98262	25
0.86434	0.97468	25
0.87224	0.97101	25
0.88527	0.96494	25
0.90356	0.95426	25
0.90619	0.95273	25
0.92712	0.93666	25
0.93491	0.92785	25
0.94805	0.91309	25
0.96627	0.87934	25
0.96898	0.87436	25
0.97222	0.86525	25
0.97543	0.85371	25
0.97861	0.84034	25
0.98176	0.82431	25

0.98487	0.80459	25
0.98796	0.7794	25
0.99102	0.74514	25
0.99404	0.69321	25
0.99703	0.59887	25
1	0	25

In the straight core annular diffuser for various swirl angle data are (at section x=0.9)

Y/Ym	U/Um	S
0	0	0
0.00289	0.54166	0
0.00581	0.6487	0
0.00877	0.70089	0
0.01175	0.73383	0
0.01476	0.75786	0
0.0178	0.7767	0
0.02087	0.79216	0
0.02397	0.80527	0
0.0271	0.81666	0
0.03027	0.82623	0
0.03377	0.83408	0
0.04799	0.86598	0
0.06572	0.89322	0
0.06586	0.89338	0
0.08345	0.91305	0

0.09795	0.92594	0
0.10117	0.9288	0
0.1189	0.94189	0
0.13002	0.94891	0
0.13662	0.95307	0
0.15435	0.96273	0
0.16209	0.96639	0
0.17208	0.97112	0
0.1898	0.97835	0
0.19414	0.97985	0
0.20753	0.98451	0
0.22525	0.98964	0
0.22617	0.98985	0
0.24298	0.99375	0
0.2582	0.99639	0
0.26071	0.99683	0
0.27843	0.9989	0
0.29021	0.99959	0
0.29616	0.99995	0
0.31388	1	0
0.32221	0.99956	0
0.33161	0.99907	0
0.34934	0.99718	0
0.35421	0.99641	0
0.36707	0.99438	0
0.38477	0.99067	0
0.38619	0.99031	0

0.40251	0.98607	0
0.41814	0.98122	0
0.42024	0.98057	0
0.43798	0.9741	0
0.45008	0.96894	0
0.45568	0.96657	0
0.47341	0.95783	0
0.48202	0.95288	0
0.49115	0.94768	0
0.50888	0.93585	0
0.51397	0.93184	0
0.52659	0.92199	0
0.54432	0.90571	0
0.54588	0.90402	0
0.56205	0.88659	0
0.57778	0.86677	0
0.57979	0.86429	0
0.59749	0.83854	0
0.60966	0.81843	0
0.61523	0.80931	0
0.63296	0.7768	0
0.64157	0.75961	0
0.65066	0.74142	0
0.6684	0.7037	0
0.67344	0.69253	0
0.68613	0.66426	0
0.70387	0.6237	0

0.70528	0.6204	0
0.72157	0.5826	0
0.73712	0.54649	0
0.7393	0.54141	0
0.75704	0.50059	0
0.76896	0.47363	0
0.77477	0.46047	0
0.79247	0.42136	0
0.8008	0.40368	0
0.81021	0.38351	0
0.82794	0.34713	0
0.83261	0.33804	0
0.84568	0.3124	0
0.86338	0.27946	0
0.86441	0.27771	0
0.88111	0.24845	0
0.89618	0.22379	0
0.89885	$2.19E\text{-}01$	0
0.91658	0.19245	0
0.92795	0.17644	0
0.93428	0.1675	0
0.95202	0.14438	0
0.95972	0.13542	0
0.96975	0.12372	0
0.9729	0.12022	0
0.97604	0.11668	0
0.97915	0.11319	0

0.98223	0.10975	0
0.98527	0.10634	0
0.98828	0.10295	0
0.99125	0.09956	0
0.99419	0.09615	0
0.9953	0.08935	0
0.99713	0.0782	0
1	0	0
0	0	7.5
0.00289	0.52215	7.5
0.00581	0.62812	7.5
0.00877	0.6812	7.5
0.01175	0.71586	7.5
0.01476	0.74184	7.5
0.0178	0.76265	7.5
0.02087	0.78002	7.5
0.02397	0.79494	7.5
0.0271	0.80803	7.5
0.03027	0.81914	7.5
0.03377	0.82826	7.5
0.04799	0.86533	7.5
0.06572	0.89633	7.5
0.06586	0.89651	7.5
0.08345	0.91813	7.5
0.09795	0.93176	7.5
0.10117	0.93478	7.5
0.1189	0.94809	7.5

0.13002	0.95497	7.5
0.13662	0.95904	7.5
0.15435	0.96818	7.5
0.16209	0.97153	7.5
0.17208	0.97585	7.5
0.1898	0.98225	7.5
0.19414	0.98355	7.5
0.20753	0.98755	7.5
0.22525	0.99183	7.5
0.22617	0.992	7.5
0.24298	0.99515	7.5
0.2582	0.99725	7.5
0.26071	0.99759	7.5
0.27843	0.99918	7.5
0.29021	0.99971	7.5
0.29616	0.99997	7.5
0.31388	1	7.5
0.32221	0.99968	7.5
0.33161	0.99931	7.5
0.34934	0.99795	7.5
0.35421	0.9974	7.5
0.36707	0.99595	7.5
0.38477	0.99336	7.5
0.38619	0.99311	7.5
0.40251	0.99019	7.5
0.41814	0.9869	7.5
0.42024	0.98646	7.5

0.43798	0.98215	7.5
0.45008	0.9788	7.5
0.45568	0.97725	7.5
0.47341	0.9717	7.5
0.48202	0.96863	7.5
0.49115	0.9654	7.5
0.50888	0.9582	7.5
0.51397	0.95581	7.5
0.52659	0.94991	7.5
0.54432	0.9402	7.5
0.54588	0.93917	7.5
0.56205	0.92863	7.5
0.57778	0.91616	7.5
0.57979	0.9146	7.5
0.59749	0.89738	7.5
0.60966	0.88277	7.5
0.61523	0.87619	7.5
0.63296	0.85043	7.5
0.64157	0.83556	7.5
0.65066	0.81991	7.5
0.6684	0.78491	7.5
0.67344	7.74E-01	7.5
0.68613	0.74617	7.5
0.70387	0.70459	7.5
0.70528	0.7011	7.5
0.72157	0.66117	7.5
0.73712	0.62219	7.5

0.7393	0.61671	7.5
0.75704	0.572	7.5
0.76896	0.54214	7.5
0.77477	0.52757	7.5
0.79247	0.48393	7.5
0.8008	0.4641	7.5
0.81021	0.44146	7.5
0.82794	0.40047	7.5
0.83261	0.3902	7.5
0.84568	0.36124	7.5
0.86338	0.32394	7.5
0.86441	0.32196	7.5
0.88111	0.28877	7.5
0.89618	0.2608	7.5
0.89885	0.25584	7.5
0.91658	0.22522	7.5
0.92795	0.20704	7.5
0.93428	0.19688	7.5
0.95202	0.17057	7.5
0.95972	0.16032	7.5
0.96975	0.14692	7.5
0.9729	0.14289	7.5
0.97604	0.13877	7.5
0.97915	0.13469	7.5
0.98223	0.13062	7.5
0.98527	0.12654	7.5
0.98828	0.1224	7.5

0.99125	0.11814	7.5
0.99419	0.11363	7.5
0.9953	0.10585	7.5
0.99713	0.09308	7.5
1.070813	0.31775	7.5
0	0	12
0.00289	0.49285	12
0.00581	0.59476	12
0.00877	0.64491	12
0.01175	0.67786	12
0.01476	0.7028	12
0.0178	0.72301	12
0.02087	0.74009	12
0.02397	0.75494	12
0.0271	0.76814	12
0.03027	0.7795	12
0.03377	0.78911	12
0.04799	0.82814	12
0.06572	0.86235	12
0.06586	0.86255	12
0.08345	0.88729	12
0.09795	0.90331	12
0.10117	0.90686	12
0.1189	0.92286	12
0.13002	0.93128	12
0.13662	0.93627	12
0.15435	0.9477	12

0.16209	0.952	12
0.17208	0.95753	12
0.1898	0.96601	12
0.19414	0.9678	12
0.20753	0.97331	12
0.22525	0.97956	12
0.22617	0.97983	12
0.24298	0.98484	12
0.2582	0.98863	12
0.26071	0.98925	12
0.27843	0.99283	12
0.29021	0.9947	12
0.29616	0.99564	12
0.31388	0.99772	12
0.32221	0.99837	12
0.33161	0.99911	12
0.34934	0.99986	12
0.35421	0.9999	12
0.36707	1	12
0.38477	0.99957	12
0.38619	0.99949	12
0.40251	0.9986	12
0.41814	0.99729	12
0.42024	0.99711	12
0.43798	0.99513	12
0.45008	9.93E-01	12
0.45568	0.99267	12

0.47341	0.98972	12
0.48202	0.98804	12
0.49115	0.98626	12
0.50888	0.98227	12
0.51397	0.98094	12
0.52659	0.97766	12
0.54432	0.97231	12
0.54588	0.97176	12
0.56205	0.96604	12
0.57778	0.95935	12
0.57979	0.95851	12
0.59749	0.94921	12
0.60966	0.94101	12
0.61523	0.93732	12
0.63296	0.92171	12
0.64157	0.91158	12
0.65066	0.901	12
0.6684	0.87408	12
0.67344	0.86452	12
0.68613	0.84053	12
0.70387	0.80099	12
0.70528	0.79742	12
0.72157	0.75679	12
0.73712	0.71531	12
0.7393	0.70949	12
0.75704	0.66049	12
0.76896	0.62716	12

0.77477	0.61091	12
0.79247	0.56161	12
0.8008	0.53902	12
0.81021	0.51324	12
0.82794	0.46632	12
0.83261	0.45452	12
0.84568	0.42125	12
0.86338	0.37831	12
0.86441	0.37602	12
0.88111	0.33776	12
0.89618	0.30549	12
0.89885	0.29977	12
0.91658	0.26444	12
0.92795	0.24346	12
0.93428	0.23174	12
0.95202	0.20137	12
0.95972	0.18949	12
0.96975	0.17396	12
0.9729	0.16925	12
0.97604	0.16443	12
0.97915	0.15962	12
0.98223	0.15479	12
0.98527	0.14989	12
0.98828	0.14484	12
0.99125	0.13949	12
0.99419	0.13357	12
0.9953	0.12457	12

0.99713	0.10982	12
1	0	12
0	0	17
0.00289	0.44467	17
0.00581	0.53814	17
0.00877	0.58171	17
0.01175	0.61026	17
0.01476	0.63198	17
0.0178	0.64978	17
0.02087	0.66502	17
0.02397	0.67847	17
0.0271	0.6906	17
0.03027	0.7012	17
0.03377	0.71059	17
0.04799	0.74881	17
0.06572	0.78529	17
0.06586	0.78552	17
0.08345	0.81409	17
0.09795	0.83384	17
0.10117	0.83822	17
0.1189	0.85906	17
0.13002	0.87058	17
0.13662	0.8774	17
0.15435	0.89372	17
0.16209	0.9001	17
0.17208	0.90833	17
0.1898	0.92146	17

0.19414	0.92434	17
0.20753	0.93324	17
0.22525	9.44E-01	17
0.22617	0.94431	17
0.24298	0.95327	17
0.2582	0.96049	17
0.26071	0.96168	17
0.27843	0.9691	17
0.29021	0.97343	17
0.29616	0.9756	17
0.31388	0.98123	17
0.32221	0.98349	17
0.33161	0.98603	17
0.34934	0.99005	17
0.35421	0.99096	17
0.36707	0.99334	17
0.38477	0.99592	17
0.38619	0.99608	17
0.40251	0.99785	17
0.41814	0.999	17
0.42024	0.99915	17
0.43798	0.99986	17
0.45008	0.99996	17
0.45568	1	17
0.47341	0.99959	17
0.48202	0.99912	17
0.49115	0.99863	17

0.50888	0.99712	17
0.51397	0.99652	17
0.52659	0.99504	17
0.54432	0.99232	17
0.54588	0.99202	17
0.56205	0.9889	17
0.57778	0.98509	17
0.57979	0.98461	17
0.59749	0.97921	17
0.60966	0.97446	17
0.61523	0.97232	17
0.63296	0.96331	17
0.64157	0.95741	17
0.65066	0.95125	17
0.6684	0.93488	17
0.67344	0.92858	17
0.68613	0.91283	17
0.70387	0.88412	17
0.70528	0.88125	17
0.72157	0.84864	17
0.73712	0.81231	17
0.7393	0.80723	17
0.75704	0.76141	17
0.76896	0.72868	17
0.77477	0.71274	17
0.79247	0.66262	17
0.8008	0.63905	17

0.81021	0.61216	17
0.82794	0.56222	17
0.83261	0.54947	17
0.84568	0.5135	17
0.86338	0.46649	17
0.86441	0.46396	17
0.88111	0.42163	17
0.89618	0.38556	17
0.89885	0.37916	17
0.91658	0.33931	17
0.92795	0.31541	17
0.93428	0.30206	17
0.95202	0.26701	17
0.95972	0.25301	17
0.96975	0.23472	17
0.9729	0.22906	17
0.97604	0.2232	17
0.97915	0.21729	17
0.98223	0.21126	17
0.98527	0.20501	17
0.98828	0.19835	17
0.99125	0.19096	17
0.99419	0.18208	17
0.9953	0.17034	17
0.99713	0.15108	17
1	0	17
0	0	25

0.00289	0.36633	25
0.00581	0.44142	25
0.00877	0.47154	25
0.01175	0.49154	25
0.01476	0.50705	25
0.0178	0.52002	25
0.02087	0.53135	25
0.02397	0.54156	25
0.0271	0.55094	25
0.03027	0.55929	25
0.03377	0.56711	25
0.04799	0.59894	25
0.06572	0.63232	25
0.06586	0.63255	25
0.08345	0.66091	25
0.09795	0.68193	25
0.10117	0.6866	25
0.1189	0.71022	25
0.13002	0.72404	25
0.13662	0.73224	25
0.15435	0.75295	25
0.16209	0.7615	25
0.17208	0.77253	25
0.1898	0.7911	25
0.19414	0.79543	25
0.20753	0.80876	25
0.22525	0.82555	25

0.22617	0.82638	25
0.24298	0.84152	25
0.2582	0.85455	25
0.26071	0.85669	25
0.27843	0.87109	25
0.29021	0.88015	25
0.29616	0.88472	25
0.31388	0.89759	25
0.32221	0.90328	25
0.33161	0.9097	25
0.34934	0.92104	25
0.35421	0.92395	25
0.36707	0.93163	25
0.38477	0.94144	25
0.38619	0.94215	25
0.40251	0.95049	25
0.41814	0.95778	25
0.42024	0.95876	25
0.43798	0.96627	25
0.45008	0.97088	25
0.45568	0.97301	25
0.47341	0.97899	25
0.48202	0.98153	25
0.49115	0.98421	25
0.50888	0.9887	25
0.51397	0.98978	25
0.52659	0.99245	25

0.54432	0.99547	25
0.54588	0.99567	25
0.56205	0.99775	25
0.57778	0.9991	25
0.57979	0.99927	25
0.59749	1	25
0.60966	0.9999	25
0.61523	0.99985	25
0.63296	0.99868	25
0.64157	0.99751	25
0.65066	0.99626	25
0.6684	0.9922	25
0.67344	0.9904	25
0.68613	0.98587	25
0.70387	0.97631	25
0.70528	0.97517	25
0.72157	0.96221	25
0.73712	0.94456	25
0.7393	0.9421	25
0.75704	0.91488	25
0.76896	0.89163	25
0.77477	0.88035	25
0.79247	0.83943	25
0.8008	0.81805	25
0.81021	0.7937	25
0.82794	0.74488	25
0.83261	0.7317	25

0.84568	0.69456	25
0.86338	0.64394	25
0.86441	0.64113	25
0.88111	0.59405	25
0.89618	0.55286	25
0.89885	0.54556	25
0.91658	0.49896	25
0.92795	0.47037	25
0.93428	0.45439	25
0.95202	0.41128	25
0.95972	0.39336	25
0.96975	0.36997	25
0.9729	0.36247	25
0.97604	0.35455	25
0.97915	0.3464	25
0.98223	0.33787	25
0.98527	0.3287	25
0.98828	0.31845	25
0.99125	0.30619	25
0.99419	0.28923	25
0.9953	0.27145	25
0.99713	0.24228	25
1	0	25

Chapter 5

FORMULATION OF UNIVERSAL EQUATION

Introduction

In order to carry on with my project, I was directed to make use of a CFD related software, a kind of equation solver, which forms graphs for the data given and forms the different equations.

This software is called **MINITAB.** The software is basically centered around the regression plots of the various data, in numerous forms and ways. It can also form the various equations which may either be linear or non linear, depending upon the type of the data in question.

5.1 Welcome to MINITAB

MINITAB is a powerful statistical software package that provides a wide range of data analysis and graphics capabilities; intuitive user interface; clean, clear output; procedure-specific statistical guidance; and extensive,

context-sensitive online help. Whether used in industry, research, or teaching, MINITAB offers the ideal combination of power, accuracy, and ease of use to help you do job better.

At a glance, MINITAB offers the following:

- Comprehensive statistics capabilities, including exploratory data analysis, basic statistics, regression, analysis of variance, sample size and power

calculations, multivariate analysis, nonparametric, time series, cross-tabulations, and simulations and distributions.

- Stat Guide—Statistical guidance for many of MINITAB's text-based and graphical analyses—from basic statistics, to quality assurance, to design of experiments.

- High-resolution graphics that are presentation-quality, fully editable, and include a brushing capability for identifying points on plots and pinpointing the actual data point in the Data window.

- Quality assurance and improvement features, including

– Run charts, Pareto charts, and cause-and-effect (fishbone) diagrams

– Statistical process control charts

– Historical charts

– Capability analysis

– Measurement systems analysis with Gage R&R

– Design of experiments capabilities to generate and analyze full and fractional designs, Plackett-Burman designs, Taguchi designs, response surface designs, and mixture models

– Multiple response optimizations

– Estimation of failure time distributions

– Regression with life data and accelerated life testing

- Powerful data management capabilities: Import data from other versions of MINITAB, spreadsheets, databases, and text files into a project. Link data to another application or another part of a MINITAB worksheet using Dynamic Data Exchange (DDE). Share data with your database using Open Database Connectivity (ODBC). Easily create subsets of your data.

- Project Manager: Minitab's Project Manager provides easy access to all the components of MINITAB project. You can rename worksheet columns and add columns descriptions; browse through your worksheets, graphs, and output; organize related documents and URLs; and more.

- Report Pad: A tool integrated into the Project Manager that helps you generate a report from your analysis.

- A macro facility that allows you to write a program of MINITAB commands to automate repetitive tasks or to extend MINITAB's functionality.

5.2 Regression in MINITAB

Regression analysis is used to investigate and model the relationship between a response variable and one or more predictors. MINITAB provides various least-squares and logistic regression procedures.

- Use least squares regression when your response variable is continuous.

- Use logistic regression when your response variable is categorical.

Both least squares and logistic regression methods estimate parameters in the model so that the fit of the model is optimized. Least squares minimizes the sum of squared errors to obtain parameter estimates, whereas MINITAB's logistic regression commands obtain maximum likelihood estimates of the parameters.

To do a linear regression

1 Choose **Stat** - **Regression** - **Regression**.

2 In **Response**, enter the column containing the response (Y) variable.

3 In **Predictors**, enter the columns containing the predictor (X) variables.

4 If you like, use one or more of the options listed below, then click **OK**.

You can also use this command to fit polynomial regression models. However, if you want to fit a polynomial regression model with a single predictor, you may find it more advantageous to use *Fitted Line Plot.*

Fitted Line Plot

This procedure performs regression with linear and polynomial (second or third order) terms, if requested, of a single predictor variable and plots a regression line through the data, on the actual or log10 scale. Polynomial regression is one method for modeling curvature in the relationship between a response variable (Y) and a predictor variable (X) by extending the simple linear regression model to include X2 and X3 as predictors.

Data

Enter your response and single predictor variables in the worksheet in numeric columns of equal length so that each row in your worksheet contains measurements on one unit or subject. MINITAB automatically omits rows with missing values from the calculations.

To do a fitted line plot

1 Choose **Stat** ä **Regression** ä **Fitted Line Plot**.

2 In **Response (Y)**, enter the numeric column containing the response data.

3 In **Predictor (X)**, enter the numeric column containing the predictor variable.

4 If you like, use one or more of the options listed below, then click **OK**.

Binary logistic regression, ordinal logistic regression, etc, are also different kinds of regressions obtainable in MINITAB. However, only the linear and non linear, that is fitted line plots were used here in our study.

5.3 Calculation on MINITAB

Also, we used the calculator function of the MINITAB software, to calculate the various equations and values for further regression analysis.

It was a tedious process in which we had to calculate the cubes, fourth powers, and upto the fifth powers of the data given. This data was then used in the development of further equations in non linear terms.

To calculate a mathematical expression

1 Choose **Calc** - **Calculator**.

2 In **Store result in variable**, enter the column or constant where you want to store the result of the expression. If you are creating a new column, enter a column number, such as C10 or C11, or a name that does not yet exist in the current worksheet.

3 With the cursor in **Expressions**, select variable names, buttons, and functions to build your expression. To set functions to their default values, omit the arguments at the end of the functions.

How to find out the non linear equations for higher degrees on MINITAB

1) To find the equations for up to cubic form, we can use the fitted line plot as explained earlier.

2) However, for higher degrees, we need to calculate the higher degrees of the data with the help of the calculator function in MINITAB, and then we use the regression function to form the higher degree equation.

3) This is done by using the columns with higher (cubic, fourth degree, fifth degree values) of the data and then using these columns as the predictors against the response to be found out (y- function).

After the equation is obtained on MINITAB

1) Once we obtain the equation, we find the values that this equation will give us on inputting the various predictors into the equation.

2) After making a column of the data obtained, we find the difference between these values and the observed values.

3) This is then followed by analyzing the differences by calculating the standard deviation.

4) If the deviation is low, or negligible, then we proceed further with the analysis.

5.4 Microsoft Excel

In addition to using MINITAB, we also made immense use of the Microsoft Excel worksheets, in order to understand where the graphs were being plotted about and what the nature of the graphs was.

The various steps involved were:

1) The data plotted and formed in the MINITAB was rearranged in the MS Excel worksheets.

2) The calculated equation was used up in calculating the original theoretical values of the data by putting in the values of the predictors in the equation formed up in the MINITAB.

3) This data was also arranged in the form of columns of MS Excel worksheets.

4) The charts were plotted for the observed values in the hub of the diffuser obtained therein.

5) The calculated theoretical values were then superimposed on this graph to see if the two graphs were similar in nature and whether there was any deviation.

Chapter 6

RESULTS AND OBSERVATIONS

In the present thesis subsonic turbulent flows inside the different type of annular diffusers with the help of GAMBIT and FLUENT. In different type of diffuser also varying area ratio. Analysis gives the effect of geometry on the velocity in diffuser. The following conclusions can be drawn from the results

Graph for the linear regression equation (0 degree swirl angle, at section 0.1x)
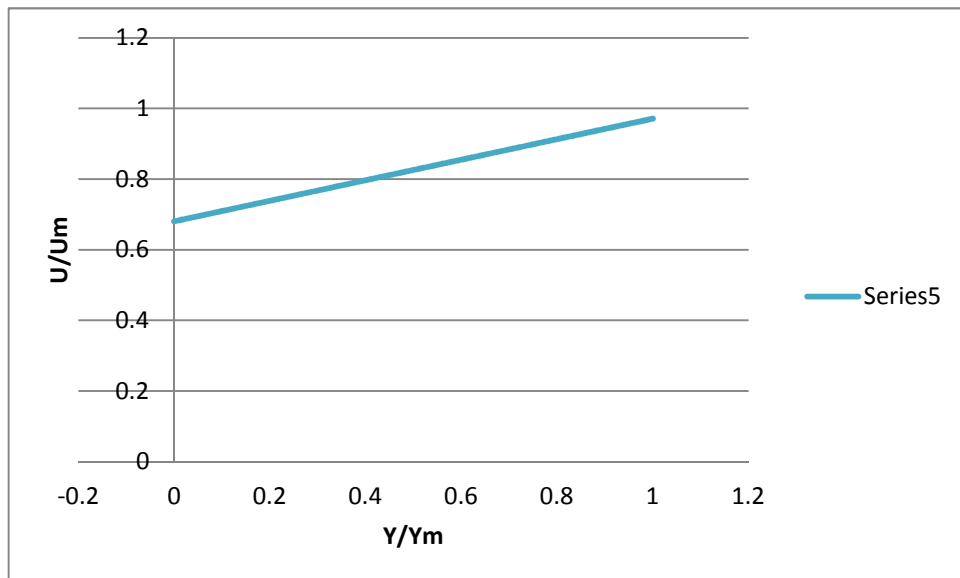
Series5- linear regression equation

Fig-3

Graph for CFD data given (0 degree swirl angle, at section 0.1x)
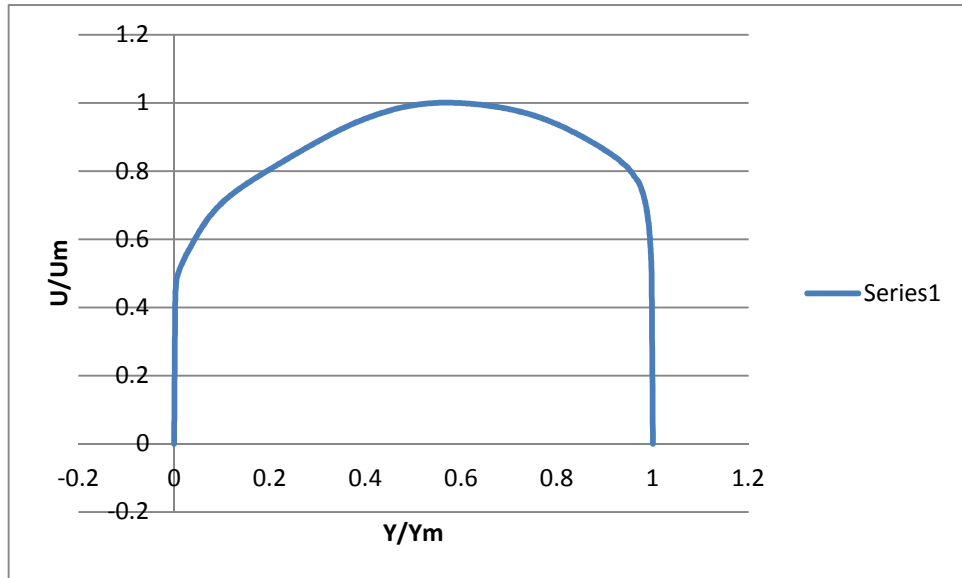
Series1- CFD Data Plot

Fig-4

Comparison between linear regression graph and CFD data graph
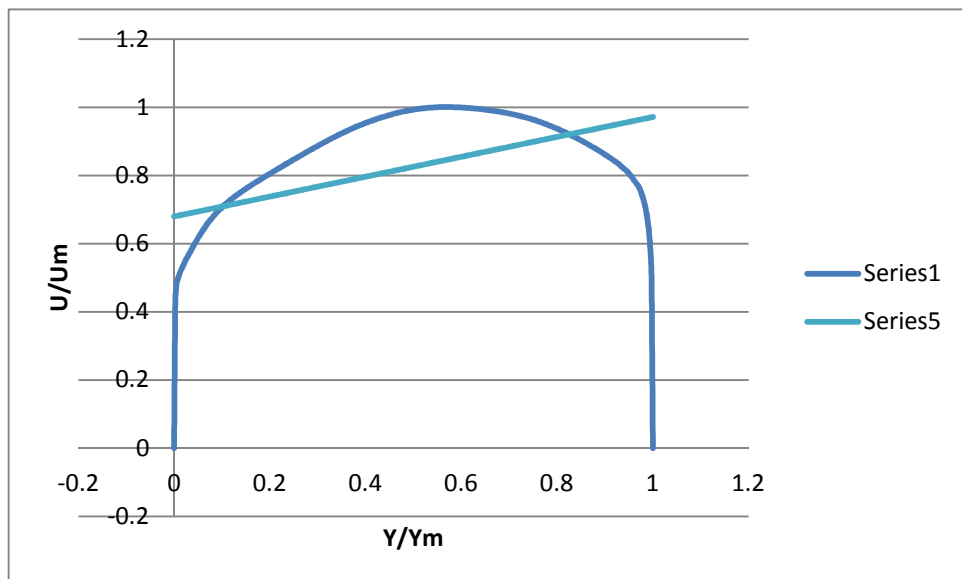
Series1-CFD Data Plot   Series5- Linear Regression Plot

Fig-5

Graph for the quadratic regression equation (0 degree swirl angle, at section 0.1x)
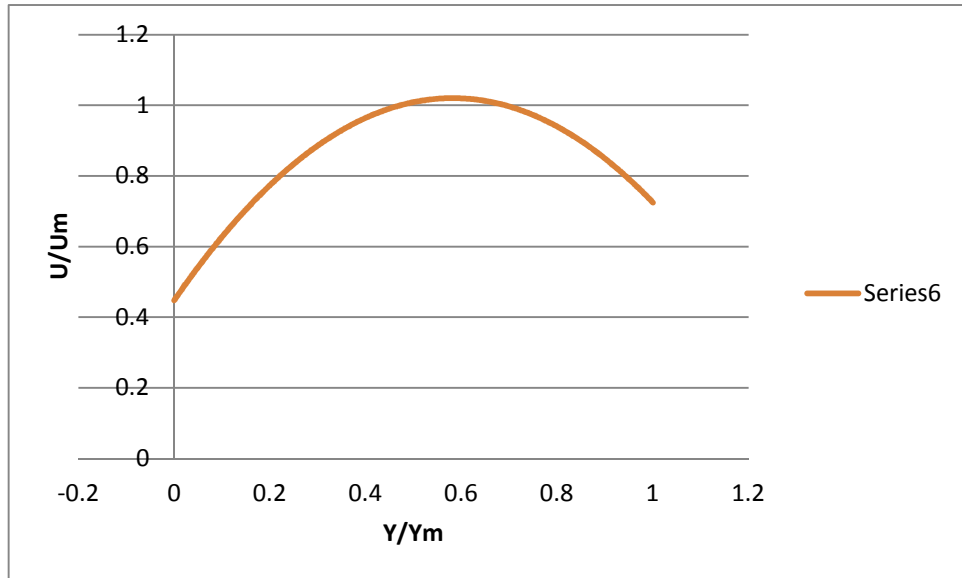
Series6- Quadratic Equation Plot
Fig-6

Comparison between quadratic regression graph and CFD data graph
(0 degree swirl angle, at section 0.1x)
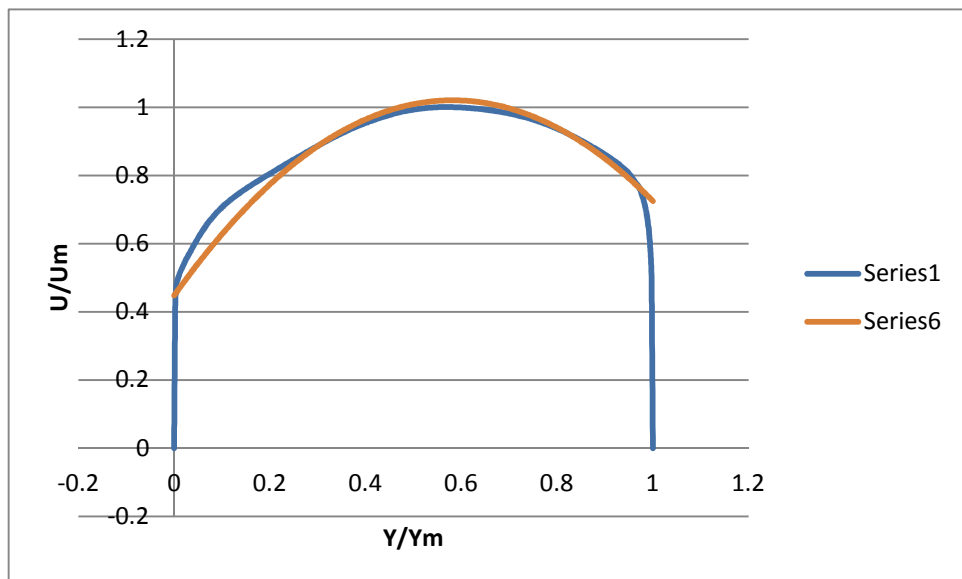
Series1-CFD Data Plot   Series6-Quadratic Equation Plot
Fig-7

Graph for the cubic regression equation (0 degree swirl angle, at section 0.1x)
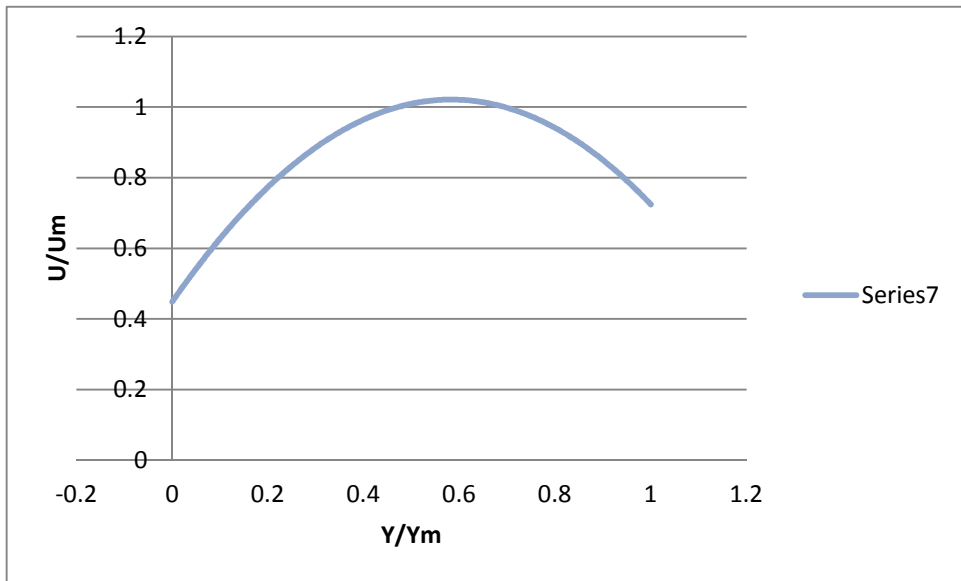
Series7-Cubic Equation Plot
Fig-8

Comparison between cubic regression graph and CFD data graph
(0 degree swirl angle, at section 0.1x)
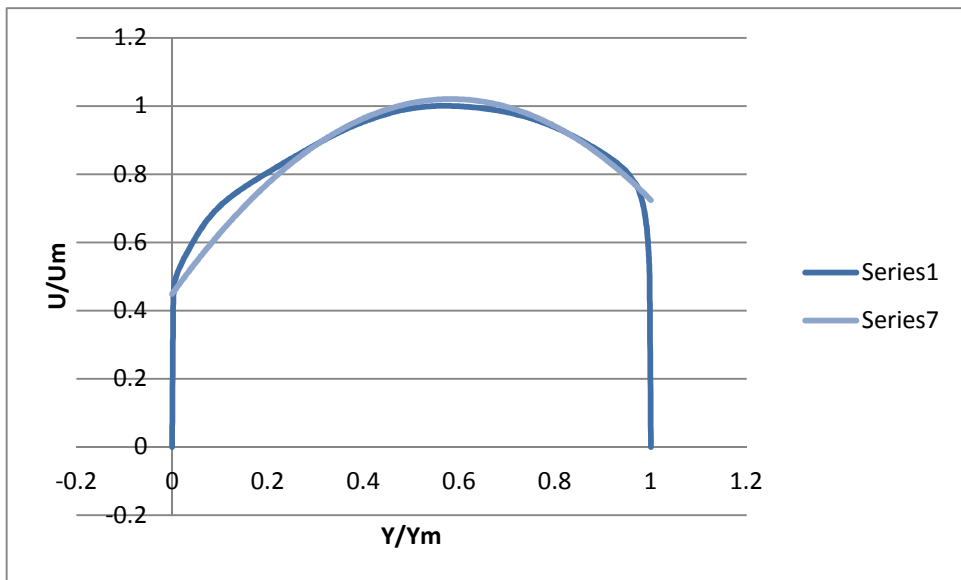
Series1-CFD Data Plot   Series7-Cubic Equation Plot
Fig 9

Graph for the biquadrate regression equation (0 degree swirl angle, at section 0.1x)
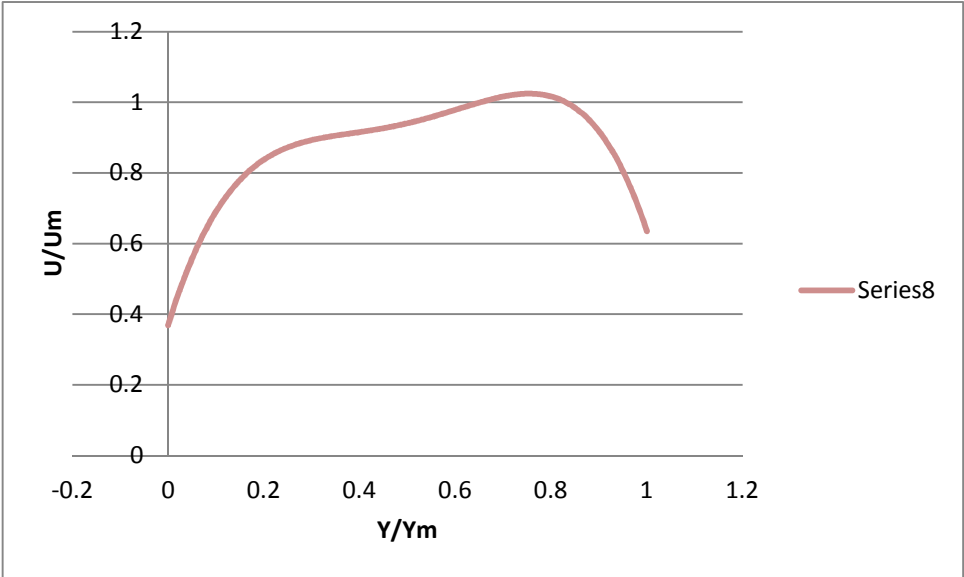
Series8- Biquadratic Equation Plot
Fig-10

Comparison between biquadrate regression graph and CFD data graph
(0 degree swirl angle, at section 0.1x)
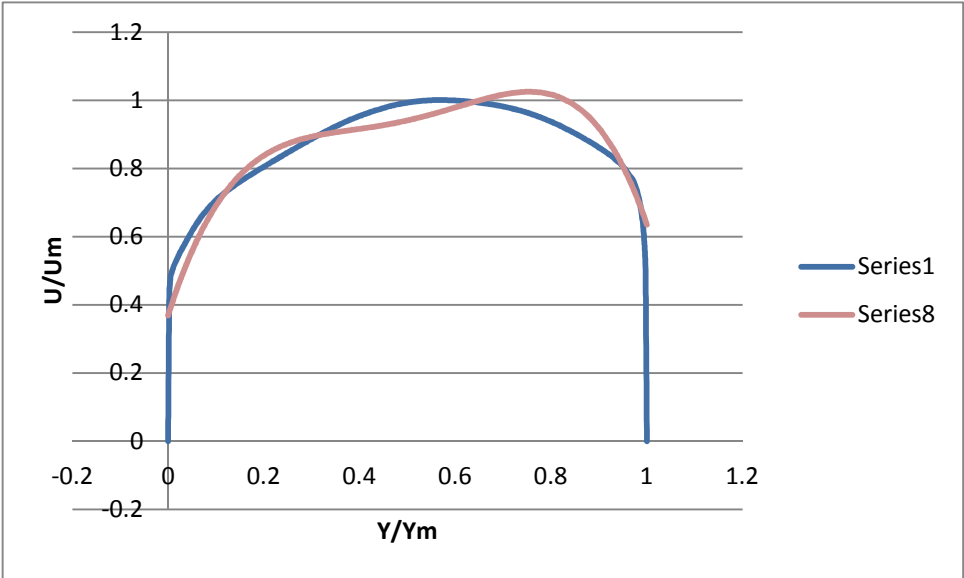
Series1-CFD Data Plot   Series8-Biquadratic Equation Plot
Fig-11

Superimposed graphs on one chart
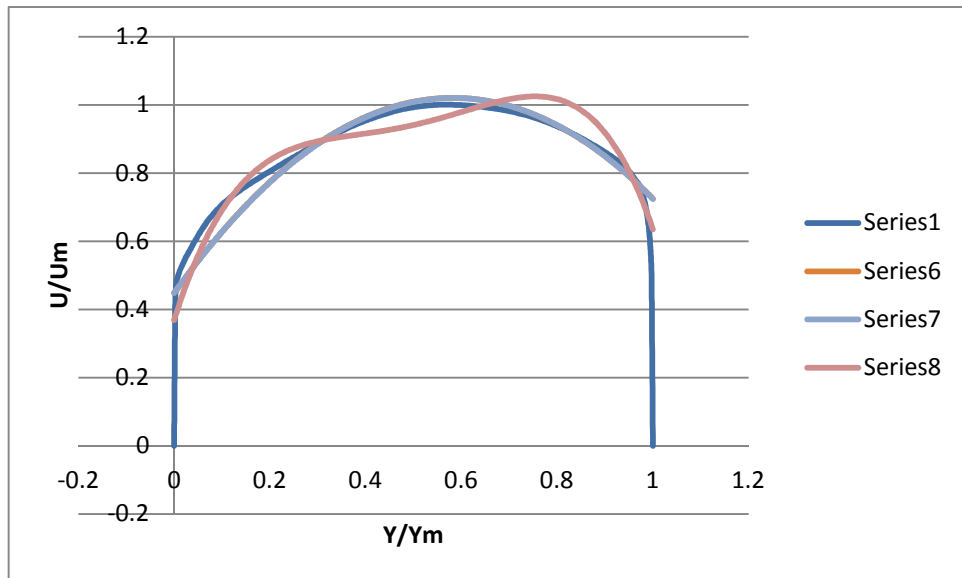
Series 1- CFD data plot   Series 2-Biquadratic Plot

Series 3 – Cubic Plot   Series 4- Quadratic Plot

Fig-12

From these charts, we find out that;

1) The cubic equation most closely follows the observed data.

2) The quadratic equation closes on the observed values of graphs but does not follow the graph as closely as possible.

3) The equation formed from the fourth power is not in tandem with the observed values.

4) Higher power equations, higher degrees, are not needed as the fourth degree equation deviates from the main values.

Various equations obtained from the regression analysis:

A) For the linear variable:

- We use MINITAB wherein the observed values are charted in the table and a regression equation obtained, as shown earlier.

- This equation is then used to obtained the calculated values from putting in the said values of Y/Ym.

- The calculated values are then re-tabulated in the MS Excel and graphs plotted accordingly.

The equation obtained is given by;

U/Um = 0.679896050+0.291406112*(Y/Ym)

A) For quadratic equation:

- The equation obtained from linear regression is then used for squaring the Right Hand Side of above equation and obtaining the squared version of U/Um (0 degree).

- However, on plotting, we see that the graph obtained is not near to the original observations.

- Hence, we use the fitted line plot function of the MINITAB and then use the values to plot the graph as well as obtain the equation.

The equation obtained on squaring linear regression equation is;

U/Um =0.488601+0.39624572*(Y/Ym)+

0.08491396*(Y/Ym)^2

The corrected equation from fitted line plot is;

U/Um=0.447269149+1.96947453*(Y/Ym)-1.69222387*(Y/Ym)^2

This 2nd equation gives the proper graph wich follows the observations.

B) For Cubic Equation:

- The graph obtained is basically an extension of the regression equation cubed to obtain the U/Um values from the regression equation obtained earlier.

- However the quadratic plot tells that using fitted line plot is a better way of obtaining the equation.

- So we use the fitted line plot function to obtain calculated values of the function.

- These values are then used to plot a graph in MS Excel.

- The graph obtained most closely follows the observed values.

  The equation obtained is;

  U/Um =0.448087601+1.95580298*(Y/Ym)-1.65536232*(Y/Ym)^2-

  0.0249087914*(Y/Ym)^3

  This equation is the best fit.

C) For Fourth degree:

- For the fourth degree of equation we need regression function as well as the values of the squares, cubes and fourth powers of (Y/Ym).

- After obtaining these values, we use the response of U/Um (0 degree) against the predictors of (Y/Ym) and its squares, cubes, and fourth powers.

- The equation obtained is then used to calculate the values of the U/Um and hence used in MS Excel to plot the graphs.

- The graph obtained is deviating more now from the real graph of observed values.

- Hence we need to stop our analysis at this stage.

The equation obtained in MINITAB is;

U/Um =0.369050979+4.42691651*(Y/Ym) -13.9869796*(Y/Ym) ^2+19.8533024*(Y/Ym) ^3-10.0271374*(Y/Ym) ^4

This equation is not closer to the observed graphs. Hence we discard this equation and observe that higher equations are more deviant. So we stop at the cubic equation.

What we need now is to obtain cubic equations through fitted line plot of MINITAB for other degrees also.

For this, we formulate the following equations (at section x=0.1)

1) For 0 Degree swirl:

   U/Um =0.452317269+2.00753657*(Y/Ym)-1.68530447*(Y/Ym)^2-0.134163177*(Y/Ym)^3

2) For 7.5 Degree swirl:

   U/Um =0.495183620+1.90208197*(Y/Ym)-1.70145320*(Y/Ym)^2+0.164208764*(Y/Ym)^3

3) For 12 Degree swirl:

$$U/Um = 0.481386605 + 1.87487665*(Y/Ym) - 1.65072511*(Y/Ym)^2 +$$

$$0.0458006999*(Y/Ym)^3$$

4) For 17 degree swirl:

$$U/Um = 0.423097198 + 2.02411771*(Y/Ym) - 1.78157300*(Y/Ym)^2 +$$

$$0.0970189234*(Y/Ym)^3$$

5) For 25 degree swirl:

$$U/Um = 0.388453313 + 1.97040203*(Y/Ym) - 1.45775581*(Y/Ym)^2 -$$

$$1.49621280*(Y/Ym)^3$$

Obtaining the universal equation for the casing part

- Thus we obtain the cubic equations for all the degrees of swirl.

- All of this analysis is concerned with the casing as of now. The hub analysis is a later part in the whole research all over the community.

- Now we need an equation which combines all the above equations to obtain a value of the single universal equation which will help us in obtaining any part of the values by putting in the values of Y/Ym as well as the corresponding degrees of swirl.

- For this we need to bring together all the equations and obtain a relation between these different coefficients of each equation as well as the degree of swirl, that is, between U/Um and the coefficients of the various degrees of Y/Ym and its powers in all the five equations.

- We input the values of these coefficients in terms of the degrees of swirl and Y/Ym and then obtain the universal equation.

The equation is obtained by;

- Tabulating the values of the coefficients of the certain power of Y/Ym against the corresponding U/Um degree.

- After this, a linear equation is then obtained between this coefficient and the degrees of swirl.

- These equations are then substituted in the place of the coefficients in the corresponding any of the equations.

- This results in the obtaining of the equation which has a universal character.

The equation obtained is between the coefficients and degrees of swirl, first;

$C0 = 0.460198176+0.00488986798*S-0.000324235814*S^2$

$C1 = 1.98734946-0.0103189424*S+0.000427985258*S^2$

$C2= -1.66217610-0.0160919591*S+0.000918587378*S^2$

$C3= -0.146049750+0.0345649054*S-0.00136417939*S^2$

By using these values in place of constants in cubic equation, we get the following equation;

$U/Um = (0.460198176+0.00488986798*S-$
$0.000324235814*S^2)+(1.98734946-$
$0.0103189424*S+0.000427985258*S^2)*(Y/Ym)+(-1.6621761-$
$0.0160919591*S+0.000918587378*S^2)*(Y/Ym)^2+(-$
$0.14604975+0.0345649054*S-0.00136417939*S^2)*(Y/Ym)^3$

This is what we can claim to be the universal equation of the casing of the annular diffuser.

1) In the straight core annular diffuser for various swirl angle graphs are(at section x=0.1)
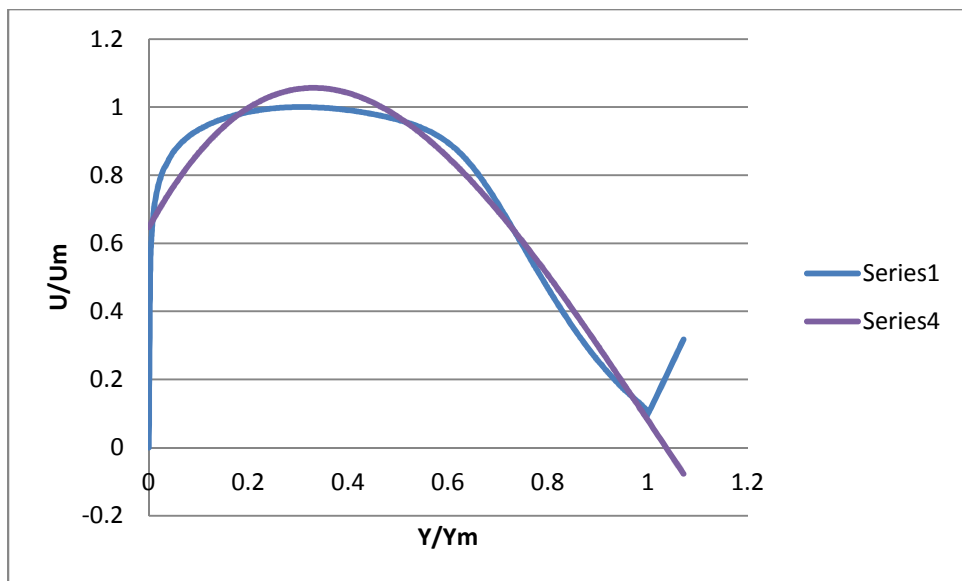
Plot for the 0 Degree Swirl
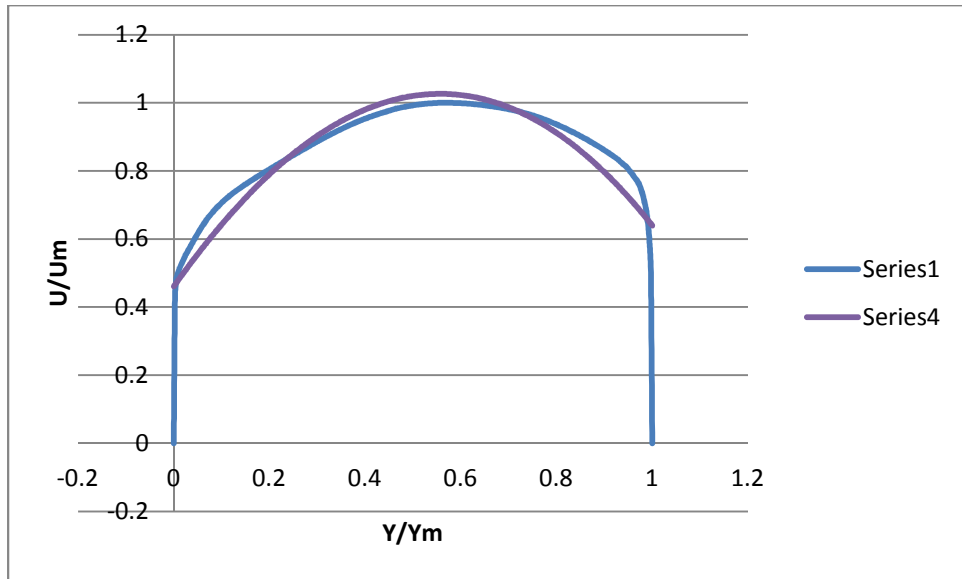
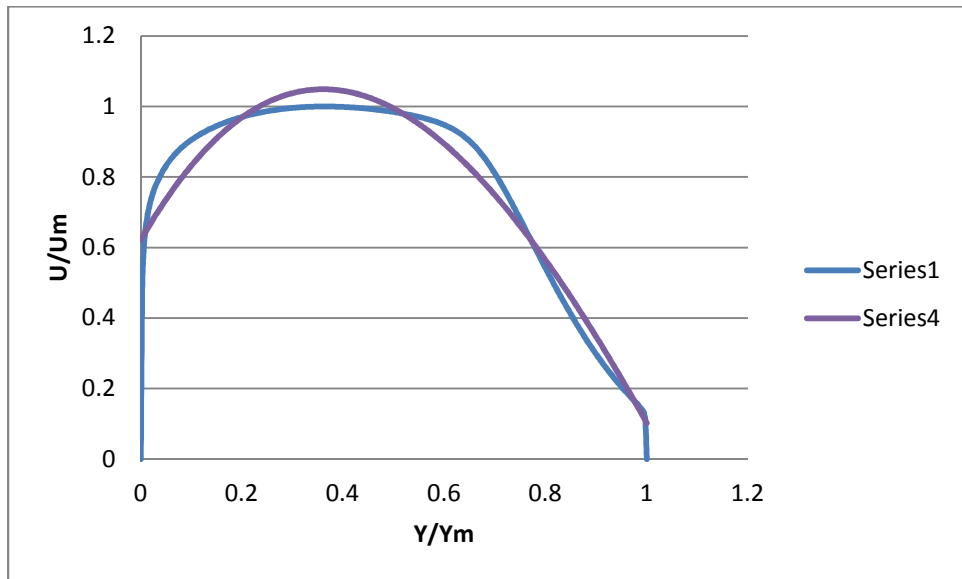Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-13

Plot for the 7.5 Degree Swirl
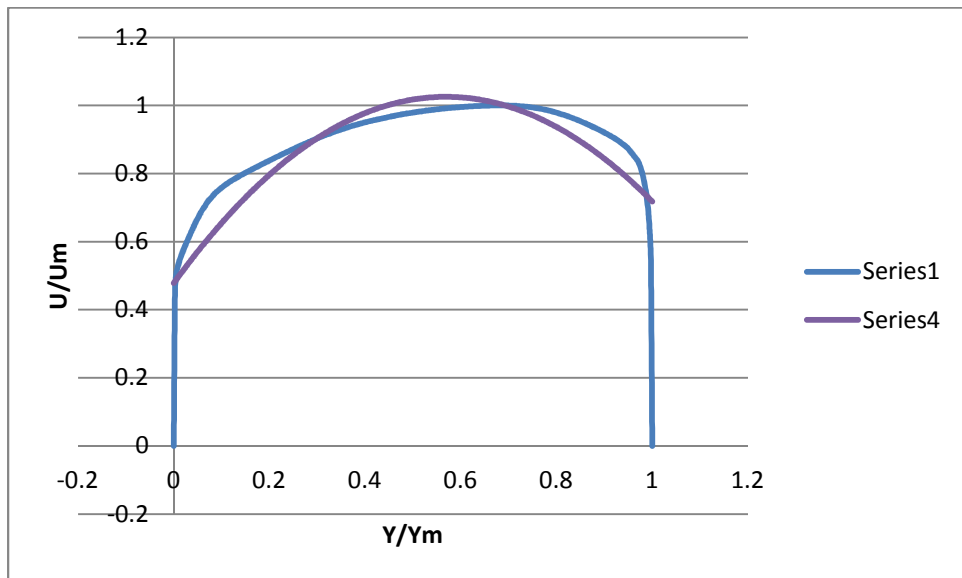
Series 1 – CFD Data Plot   Series 4 – Cubic Plot
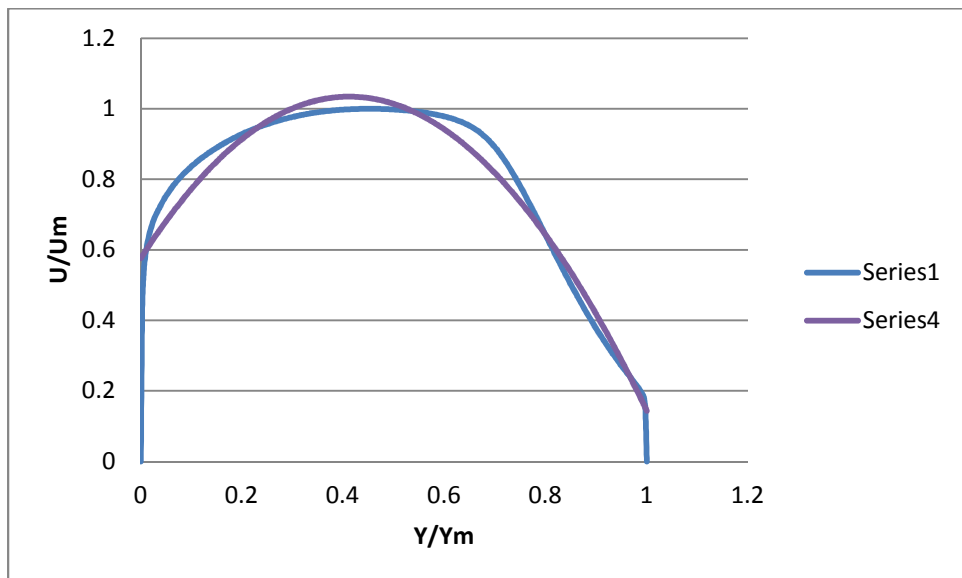
Fig-14

Plot for the 12 Degree Swirl
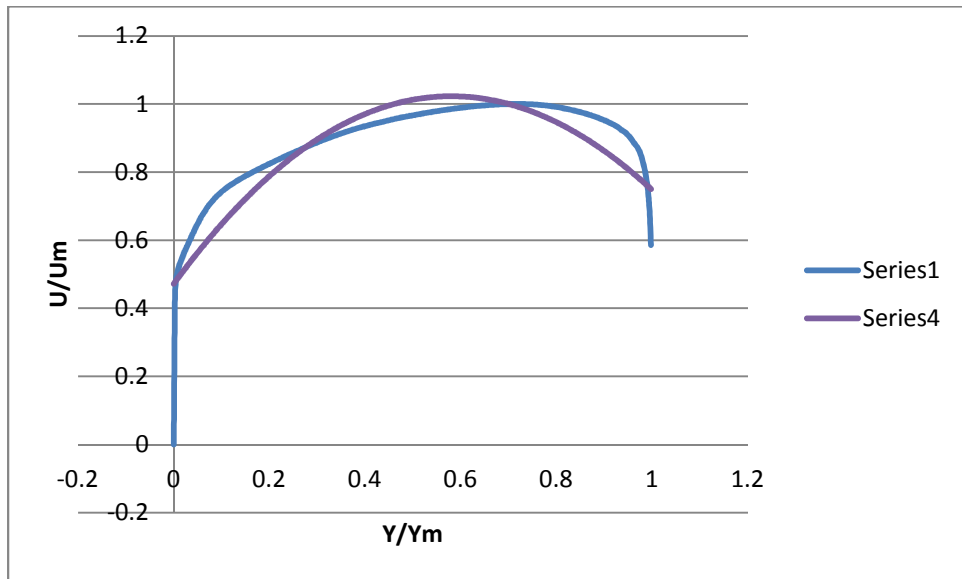
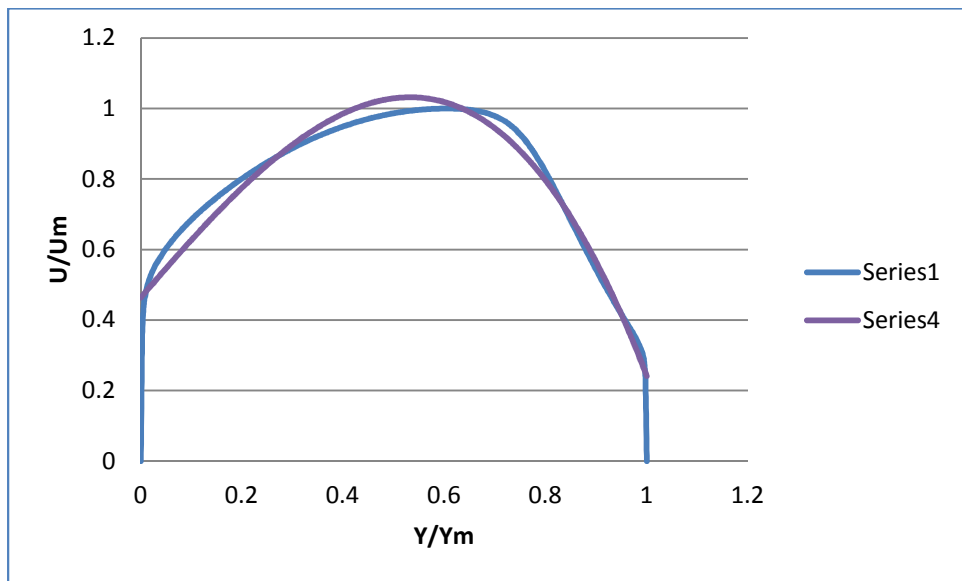Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-15

Plot for the 17 Degree Swirl
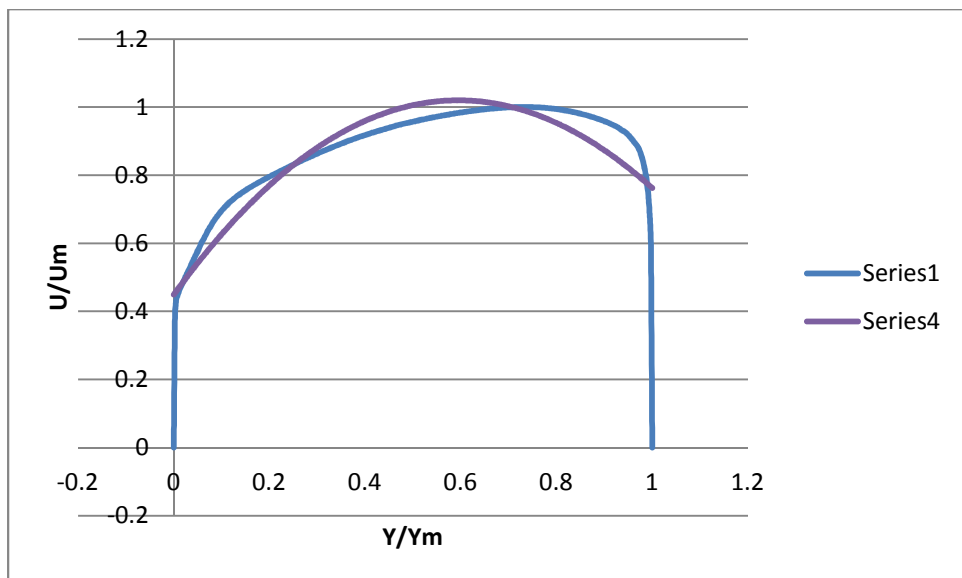
Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-16

Plot for the 25 Degree Swirl
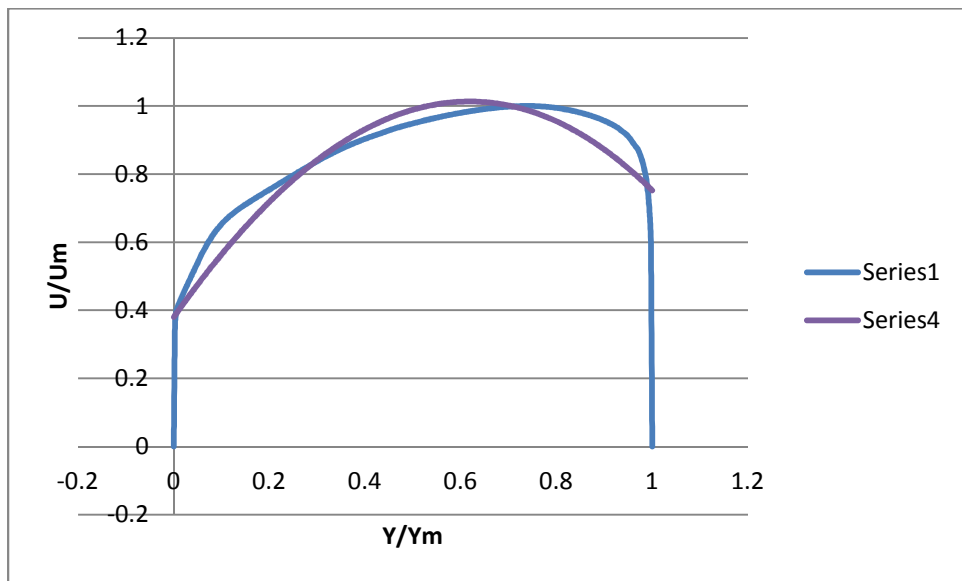
Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-17

Similarly at the section 0..9x of casing:

- The following graphs have been plotted after obtaining the universal equation
  for section 0.9x of casing.

- These equations were obtained using MINITAB and using the same procedure
  as for section 0.1x of casing.

- The equation at section x=0.9 of casing is;

U/Um =(0.655946558+0.00157632043*S-

0.000370814108*S^2)+(2.77219898-0.00332982686*S-

0.00161695515*S^2)*(Y/Ym)+(-

5.64625287+0.0669658315*S+0.00588410655*S^2)*(Y/Ym)^2+(2.28636229

-0.0662370398*S-0.00357874141*S^2)*(Y/Ym)^3

In the straight core annular diffuser for various swirl angle graphs are (at section x=0.9)

Plot for the 0 Degree Swirl
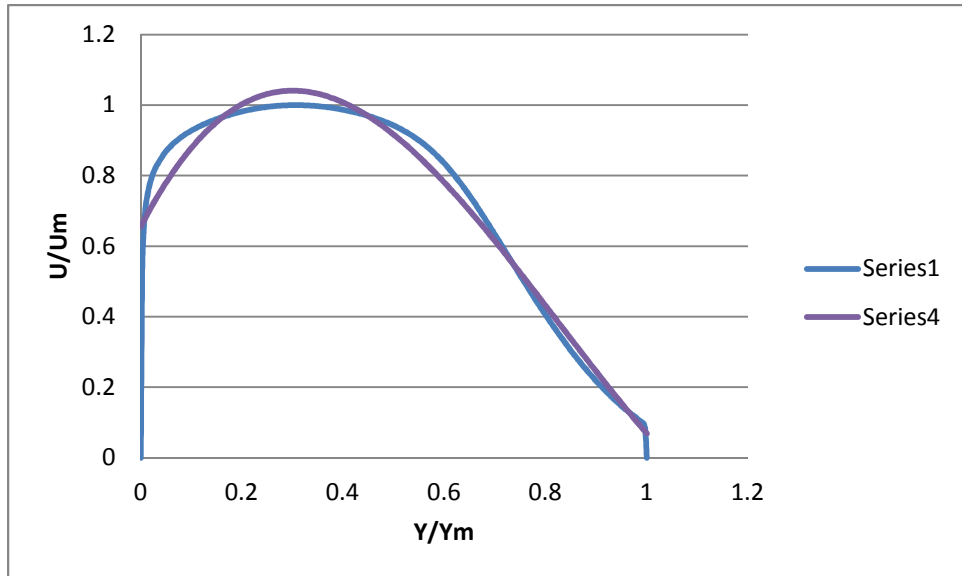
Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-18

Plot for the 7.5 Degree Swirl

Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-19

Plot for the 12 Degree Swirl

Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-20

Plot for the 17 Degree Swirl

Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-21

Plot for the 25 Degree Swirl

Series 1 – CFD Data Plot   Series 4 – Cubic Plot

Fig-22

Hence we see that the graphs obtained from the overall universal equation are almost similar and in tandem with the original observed values.

This tells us that the analysis we have carried out is proper and functional in all respects.

Now, we need to obtain all the graphs formed from the universal equation on a single chart, in order to visualize the swirl respectively.

Observed values plotted on the graph give the following type of chart distribution (at section 0.1x)
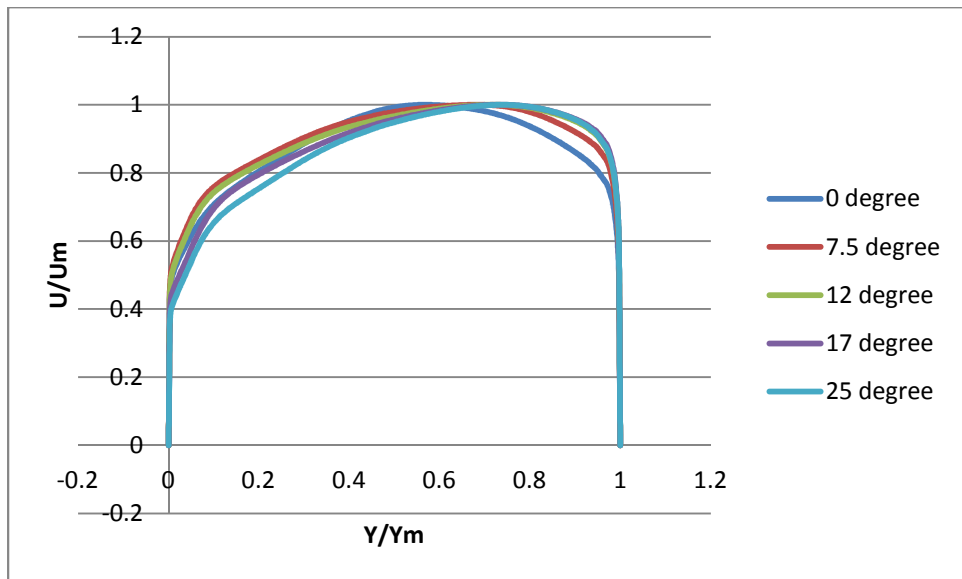
Fig-23

the values as obtained from the cubic equations solved were as given below (at section 0.1x)
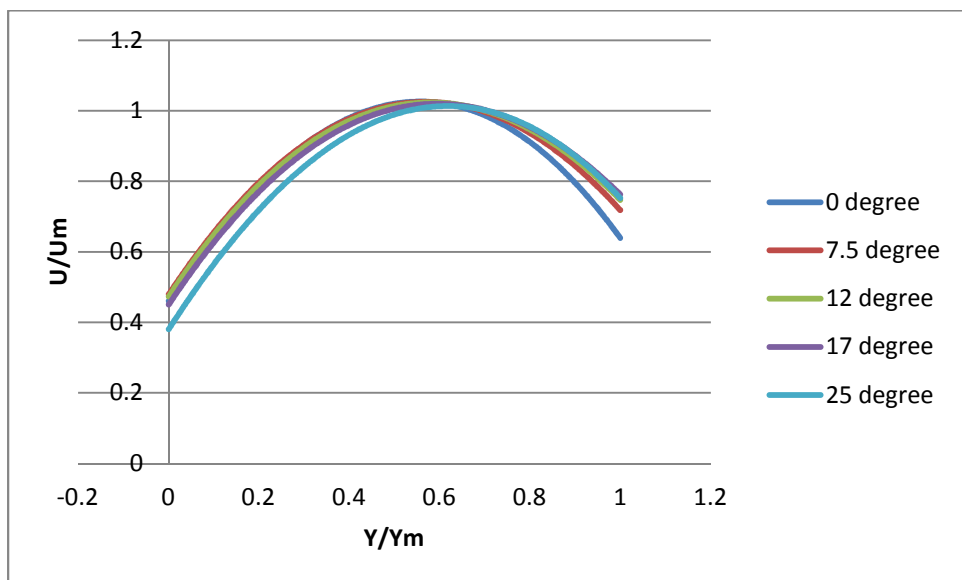
Fig-24

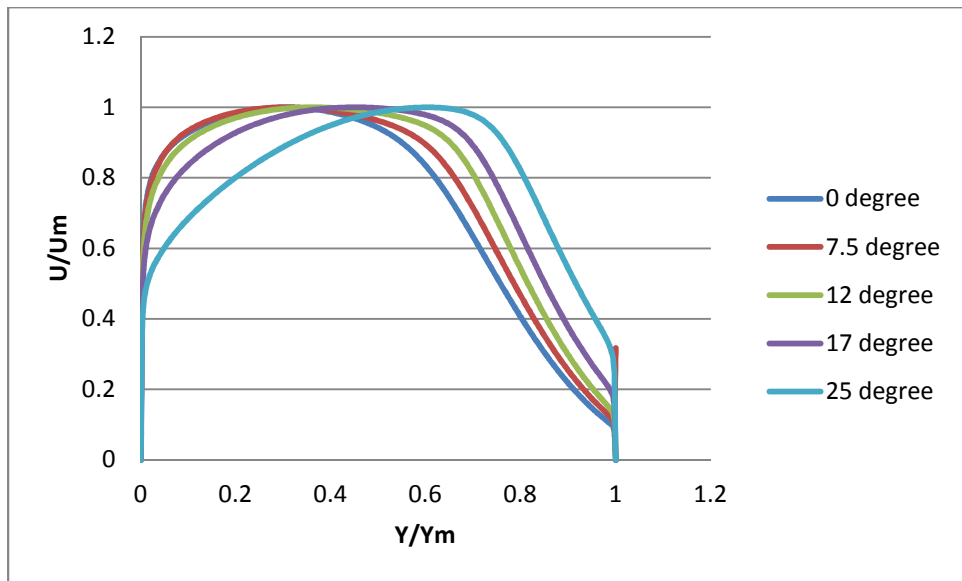Observed values plotted on the graph give the following type of chart distribution (at section 0.9x)

Fig-25

Also the values as obtained from the cubic equations solved were as given below (at section 0.9x)
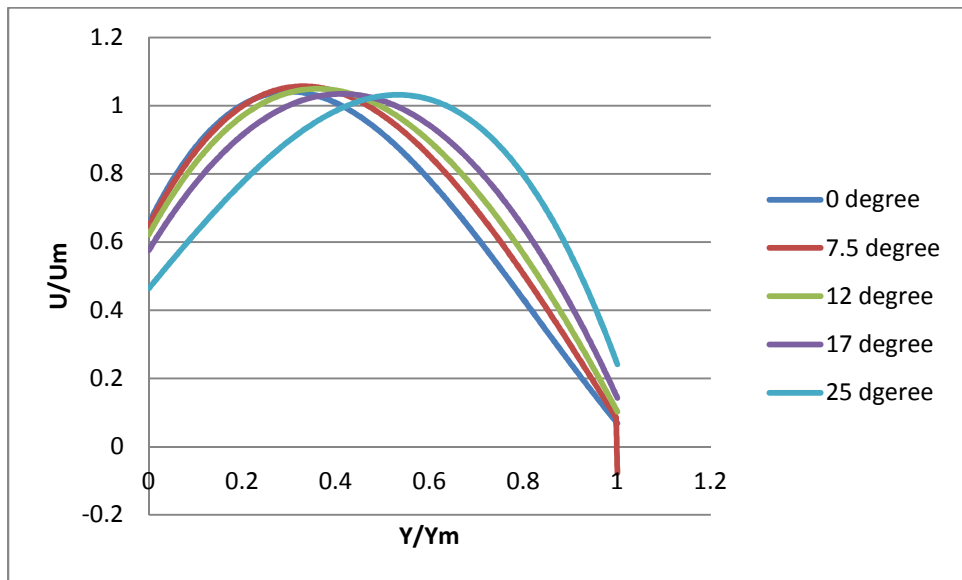

Fig-26

This agrees with both the cubic equations obtained as well as the observed values.

Hence we can conclude that the data has the universal equation as provided above.

Chapter 7

RECOMMENDATIONS FOR FUTURE WORK

- Annular diffuser in considered in the present study. Future work can be done on conical, rectangular, radial type diffusers.

- The present work was done at section x=0.1 and x=0.9 of casing. Future work can be done on different sections of casing and hub.

- The effect of hub-generated swirl can be considered for future study.

- The effect of Mach number can be studied.

- The present analysis is done for stationary hub and casing. Further studies can be done on rotating hub and casing diffuser.

- Modeling of the geometry can be modified by attaching a tailpipe at the exit to recover some of the excess kinetic energy of a non-uniform diffuser exit profile in to pressure energy.

- The present work was done for sub-sonic flow uncompressible flow only. The scope can be extended to compressible and sonic flows.

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