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Studies on Base Pressure in Suddenly Expanded Circular Ducts: a Fuzzy Logic Approach

K.M.Pandey, *Member, IACSIT* and Amit Kumar

***Abstract*-- An optimum L/D ratio is evaluated in the present study using fuzzy-set theory. The fuzzy set based methodology could easily consider many attributes concurrently, while deciding the specifications of the suddenly expanded supersonic fluid flow through a straight circular duct. The methodology can be easily extended to a situation involving diverse conflicting objectives. This study can be extended to different nozzles having different geometries with variations in Mach numbers, primary pressure ratio and area ratio. It is observed that L/D ratio is 6 for base pressure for Mach numbers of 1.58, 1.74, 2.06 and 2.23 , which is in very close agreement with the experimental results cited in the literature. This has been discussed with fuzzy logic as a tool for three area ratios 2.89, 6.00 and 10.00. The primary pressure ratio has been varied from 2.10 to 3.48 and L/D ratio has been varied from 1 to 6. From this analysis it is observed that L/D ratio 6 is the optimum needed keeping in view all the parameters like wall static pressure and pressure loss including base pressure.**

***Index Terms*—fuzzy logic, base pressure, supersonic flow, Mach number, area ratio, pressure ratio**

NOTATION

A_r Area ratio defined as the ratio of enlarged duct area to the nozzle exit area.
ASR1 Models with cavity aspect ratio 1.
ASR2 Models with cavity aspect ratio 2.
D Diameter of enlarged duct.
P_a Ambient atmospheric pressure.
P_b Non-dimensional base pressure
P_{01} Stagnation pressure in the settling chamber, also called primary pressure.
P_{01}/P_a Primary pressure ratio
L Length of enlarged duct.
M Mach number at the nozzle exit.
ST Represents enlarged duct without cavities.
R_e Reynold's number
μ_x Membership function

I. INTRODUCTION

The flow field of abrupt axi-symmetric sudden expansion is a complex phenomenon characterized by flow separation, flow recirculation and reattachment. Such a flow field may be divided by a shear layer into two main regions, one being the flow recirculation region and the other being the main flow region. The point at which the dividing streamline strikes the wall is called the reattachment point. The base pressure is the pressure in the adjacent corner of the expansion duct. Although, the value of this varies along the length but normally the average of the values are taken. In this paper the base pressure is non-dimensionalized by dividing it with the ambient pressure. Soft computing is an emerging approach to computing which parallels the remarkable ability of the human mind to reason and learn in an environment of uncertainty and imprecision. Soft computing consists of several computing paradigms, including neural networks, fuzzy set theory, approximate reasoning, and derivative- free optimization methods such as genetic algorithms and simulated annealing. For learning and adaptation, soft computing requires extensive computation. In this sense, soft computing shares the same characteristics as computational intelligence. In general, soft computing does not perform much symbolic manipulation, so we can view it as a new discipline that complements conventional artificial intelligence approaches, and vice versa. Unlike conventional algorithms, soft computing methodologies are tolerant of imprecision, uncertainty and partial truth . Soft computing techniques do not suffer from the brittleness and inflexibility of standard algorithmic approaches. Fuzzy set theory, neural networks, genetic algorithms form the part of soft computing apart from many other techniques. Fuzzy set theory derives its motivation from approximate reasoning. Neural networks get their motivation from biological nervous systems. Genetic algorithms are based on the nature's law of the "survival of the fittest". There has been a spurt of activities to integrate these techniques.

A classical set is a set with a crisp boundary. For example, a classical set A of real numbers greater than 6 can be expressed as

$$A = \{x|x > 6\},$$

Where there is a clear, unambiguous boundary such that if x is greater than this number, then x belongs to the set A: otherwise x does not belong to the set. Although classical sets are suitable for various applications and have proven to be an important tool for mathematics and computer science, they do not reflect the nature of human concepts and thoughts, which tend to be abstract and imprecise.

II. LITERATURE REVIEW

To make the problem simpler the linear function is considered throughout the methodology. The datas were collected from the experiments conducted by Pandey K.M.(20) . Moreover, in spite of the flow being supersonic the effects of shock are not being considered. In today's scenario the study about the abrupt expansion of the jet of gas is of general interest in a variety of flow systems. In most of the cases the enlarged duct used has a smooth continuous inner surface and makes use of the low base pressure that results due to the sudden relaxation of the shear layer from the inlet passage at the entry to the sudden enlargement. The base pressure and the flow field downstream of the base are dictated by the vortex dynamics triggered by the sudden expansion of the flow in the enlarged duct. There are also cases wherein the experiments on sudden expansion are conducted in a straight duct and some in straight duct with cavities. Our present study is about the optimization of the length to diameter ratio (L/D) of the straight duct in the absence of cavities with the help of a soft computing methodology, 'the Fuzzy Sets'. This work deals upon the effect of base pressure, pressure loss and wall static pressure individually. Some of the works, which are directly related to the present work, are the following. Borda [1] was the first to investigate the problem of sudden enlargement in flow of water through sudden increase in duct cross-section. Nusselt [1] conducted experiments with high velocity gas flow through ducts with sudden increase in flow cross-section. From this extensive experimental study in subsonic and supersonic flows, he concluded that the base pressure would be equal to the entrance pressure if the velocity was subsonic, but if the entrance flow was supersonic, the base pressure could be equal to or less than or greater than the entrance pressure. The effect of boundary layer on sonic flow through an abrupt cross-sectional area was experimentally studied by Wick [1]. He observed that the pressure in the corner of expansion was related to the type and thickness of boundary layer at the corner of inspection. He considered boundary layer as the source of fluid for corner flow. But in the view of Hoerner [1] the boundary layer was an insulating layer that reduces the effectiveness of the jet as a pump. The base corner was thought of as a sump with two supplies of mass. The first was the boundary flow around the corner and the second flow was the back flow in the boundary layer along the wall of the expanded section. The base flow occurred because of the pressure difference across the shock wave originating where the jet strikes the wall. He concludes that the mechanism of internal and external flow was principally the same and base pressure phenomena in external flow could be studied relatively easily by experiments with internal flow. Korst [2] investigated the problem of base pressure in transonic and supersonic flow, for the case in which the flow approaching the base is sonic or supersonic after the wake. He devised a physical flow model based on the concept of introduction between the dissipative shear flow and the adjacent free streams and the conservation of mass in the wake. These results agreed closely with the experimental data of Wick. Hall and Orme [3] studied compressible flow through a sudden enlargement in a pipe both theoretically and experimentally and showed a good arrangement between theoretical and experimental results. They developed a theory to predict Mach number in a downstream location of sudden enlargement of known values of Mach number at the exit of the inlet tube, with compressible flow assumptions; they also assumed that the pressure across the face of the enlargement was equal to the static pressure in a small tube just before the enlargement. However these assumptions are far away from reality, since it is a well-established fact that the pressure across the face I the recirculation region, namely the base pressure, is very different from the pressure in the smaller tube just before the enlargement. They studied the problem with a range of Mach numbers from 0 to 1. Benedict [4] with various other investigators analyzed the sudden enlargement problem in an elaborate manner both theoretically and experimentally. Anderson and Williams [6] worked on base pressure and noise produced by the abrupt expansion of air in a cylindrical duct. They used stagnation pressure ratio of the forcing jet to atmospheric of up to 6 for various length to diameter ratios. With an attached flow the base pressure had minimum value, which depends mainly on the duct to nozzle area ratio and on the geometry of the nozzle. The plot of overall noise showed a minimum at a jet pressure approximately equal to that required to produce minimum base pressure. Durst et al. [8] studied low Reynolds number flow over a symmetric sudden expansion. The flow was totally dependent on the Reynolds number and the nature was strongly three-dimensional at higher Reynolds number. They reported flow visualization and laser anemometry measurements. At Reynolds number 56 the separation region behind each step was of equal length but at Reynolds number 114 the two separation regions had different lengths leading to a symmetrical velocity profile. At Reynolds number 252 a third separation zone was found on one wall. There were substantial three-dimensional effects in the vicinity of the separation regions. Cherdon et al. [9] studied asymmetric flow and instabilities in symmetric ducts with sudden expansion. Asymmetric flows were caused by the disturbance generated at the edge of the expansion and amplified in the shear layers. The spectral distribution on the fluctuation in velocity is quantitatively related to the dimension of the two unequal regions of flow recirculation. They showed that the intensity of fluctuating energy in the low Reynolds numbers could be larger than the corresponding turbulent flow. Durst et al. [8] demonstrated that symmetric sudden expansion duct, for only a limited range of Reynolds number. At higher Reynolds numbers, the small disturbances generated at the tip of sudden expansion are amplifying in the shear layers formed between the main flow and the recalculation flow at the corners. This resulted in shedding of eddy like patterns which alternated from one side to other with consequent asymmetry of mean flow. Although the flow was three-dimensional, its major features could be understood by considering the interaction of two dimensional shear layers. Brady and Acrivos [10] studied cavity laminar flows at moderate Reynolds number. They suggested that the similarity solutions should be reviewed with caution because they might not represent real flow once a critical Reynolds number was exceeded. The flow field in a suddenly enlarged combustion chamber was studied experimentally by Yang and Yu [11]. The combustion chamber consisted of circular Plexiglas with a suddenly enlarged section followed by a nozzle. The Reynolds number based on the inlet duct diameter and center velocity was 64,000. The wall pressure measurement was carried out with laser Doppler anemometer. Detailed profiles of main velocities of turbulent intensities, turbulent shear stresses and wall pressure distribution were developed. The dividing stream line, reattachment point and the magnitudes of the mean kinetic energy and turbulent kinetic were also determined. The authors observed that the laser Doppler anemometer with a frequency shifter was a useful instrument for measuring reverse flow fields especially for the highly turbulent flow field encountered in the study.

Measurements from a conventional hot ire anemometer might present considerable error. Raghunathan and Mabey [12] studied passive shock wave/boundary layer control on a wall-mounted model. They evaluated the effects of orientation, normal forward facing and backward facing. The porosity used was 1.6%. Their measurement included static and dynamic pressure on the model surface and wake traverse. They had visualized the field with shadowgraphs. The forward facing holes located around shock position showed an appreciable decrease in drag compared with solid surface model. Raghunathan [13] studied pressure fluctuation with passive shock position showed an appreciable decrease in drag compared with solid surface model. Raghunathan [14] also studied pressure fluctuation. with passive shock/ boundary layer control and found that the forward facing holes configuration with a porosity of 1-2% produces maximum drag reduction. Wilcox Jr. [15] studied the passive venting system for modifying cavity flow fields at supersonic speed. Experimentally he showed that a passive venting system could be employed to control cavity flow field at supersonic speed, specifically the passive venting system had been used to extend the L/H value before the onset value of high drag producing closed cavity flow. In his experiment the porous flow eliminated the large drag increase for L/H >12. There is tremendous increase in drag coefficient for L/H > 12 but for porous flow having more diameters the decrease in drag coefficient is comparatively very less with the floor having fewer diameters. Tanner [16] studied base cavity at angle of incident. He concluded that the base cavity could increase the base pressure and thus decrease the base drag in axi-symmetric flow. He varied the angle of incident from 0 to 25 degrees. At alpha = 2 degree he found that the maximum drag decreased. Rathakrishnan et al. [17] studied the influence of cavities on suddenly expanded flow fields experimentally. Based on their study of air flow through a convergent axi-symmetric nozzle expanding suddenly into a annular circular parallel shroud with annular cavities, they concluded that smoothening effect by the cavities on the main flow field in the enlarged duct was well pronounced for the large ducts and the cavity aspect ratio has a significant effect on the flow field as well as on the base pressure. The results showed that increase in cavity aspect ratio from 2 to 3 results in base pressure, but for increase in aspect ratio from 3 to 4, the base pressure goes up. The effectiveness of a passive device for axi-symmetric base drag reduction at Mach 2 was studied by vishwanath and patil [18]. The device examined included primary base cavities and ventilated cavities. Their results showed that the ventilated cavities offered significant base drag reduction. They found 50% increase in base pressure and 3-5% net drag reduction at supersonic Mach number body of revolution. Kruiswyk and Dutton [19] studied the effects of base cavities on subsonic near wake flow. They experimentally investigated the effects of the base cavity on the near wake flow field of a slender two-dimensional body in the subsonic speed range. Their basic configurations were studied and compared were a blunt base, a shallow rectangular cavity base of depth equal to ½ of the base height and a deep rectangular cavity base of depth equal to base height. Schlieren photographs revealed that the basic qualitative structure of the vortex street was unmodified by the presence of base cavity. The weaker vortex street yielded higher pressure in the near wake for the cavity base, increase in the base pressure coefficient of the order 10-14% and increase in the shedding frequencies of the order of 4-6% relative to the blunt based configuration. Air flow from a mach 1.74 convergent-divergent axi-symmetric nozzle expanded suddenly into circular duct of larger cross-sectional area, provided with annular rectangular cavities, was studied experimentally by Pandey, K.M. and Rathakrishnan E. [20], focusing attention to the base pressure, and the flow development in the enlarged duct. It was found that the pressure is strongly influenced by the expansion level at the nozzle exit, the area ratio of the passage, the L/D ratio of the enlarged duct. For low area ratio, the annular cavities result in increase in the base pressure. Also, the cavity aspect ratio influences the base pressure significantly for low area ratio. Supersonic jet flow from convergent divergent nozzle with method of characteristics contour expanding suddenly into circular pipes with and without annular cavities was experimentally investigated by Pandey, K.M. [21], for Mach number 1.74. Attention was focused on variation of non dimensional base pressure and oscillations of base pressure. It was observed that the base flow is wave dominated for L/D ratio up to 4 only with mild oscillations. It was observed that increasing L/D ratio beyond 6 does not have any effect on the base pressure and the base pressure is minimum for models without cavity and maximum for the models with cavities of aspect ratio 2. Flow from nozzles expanding suddenly into circular pipes with and without annular cavities was experimentally investigated by Pandey, K.M., [22] for Mach number range of 1.00 – 2.75. The base pressure was found increasing with increasing Mach number's as expected for supersonic Mach numbers. The effect of aspect ratio on base pressure is only marginal for supersonic Mach number's. Flow from nozzles expanding suddenly into circular pipes with and without annular cavities was experimentally investigated by Pandey, K.M. [23], for a Mach number range of 0.60 to 2.75. The pressure loss was found increasing with increasing mach numbers. Total pressure loss increases with increase in Mach number, primary pressure ratio, area ratio and L/D ratio. In supersonic regime pressure loss increases for models with cavities aspect ratio 1 and decreases for models with cavity aspect ratio 2 for L/D ratio up to 4. Airflow from convergent axi-symmetric nozzle expanded suddenly into circular duct of larger cross-sectional area was studied experimentally, by Pandey, K.M., Khan, S.A., and Rathakrishnan E. [24]. They focused their attention on base pressure, the flow development in the enlarged duct and the pressure loss. It was found that the base pressure is strongly influenced by the parameter viz. the nozzle exit mach no, the area ratio of the passage, the length to diameter ratio of the enlarged duct. The base pressure decreases with increase in Mach number. The base pressure was found to be smooth and without oscillation in the Mach number range of 0.6-1.0. Dixit and Dixit [25] applied Fuzzy Set theory in Scheduling of a tandem cold- rolling mill. This gives a clear concept of using a fuzzy set theory in various fields of interest. They have worked on optimizing the power consumed and maximum reliability together by considering the various constraints like, interring stand tensions, rolling speed, and rolling pressure and forces, and thickness of the strip at exit of each stand. Even though all those parameters where considered to be related to power consumed they were all assumed constant for a particular speed and particular inter stand thickness. In his procedure with experimental data available he calculated the optimal power for those data, by deriving a relation for power and reliability. Rathakrishnan [26] demonstrated that a control in the form of annular ribs could serve as an effective controller to control the base pressure for axi-symmetric sudden expansion of under expanded sonic flows. It was found that the rib, when placed at an appropriate location downstream of the base prevents the reverse flow through boundary layer into the base zone. This enables the free-shear layer expanding at the base to have its process delinked from influence of the reverse flow. The same principle is going to be applied in our project also. Dixit, Robi and Sharma [27] studied a systematic study for design of cold rolling mill. The design of a cold rolling mill is calculated by considering many factors like roll velocity, power, reliability, running cost, roll torque, and roll radius. With this paper we can learn a clear idea of creating a membership function for any criteria. Abburi and Dixit [28] together generated a knowledge-based system for predicting the surface roughness in turning process. In which they generated IF-THEN rules using Fuzzy set theory. Soft computing-based techniques are used to impart capabilities. Pandey, K.M, and Rathakrishnan E. [29,30] studied on flow characteristics of a subsonic, sonic and as well as supersonic flow through a circular duct provided with annular ducts. The experiment was conducted on various pressure ratios and area ratios. The base pressure, pressure loss and wall static pressure was calculated and they studied the effects caused on the circular ducts. They found that the flow was not attached for small L/D wherein the flow showed oscillatory pressure in a large L/D and moreover losses increased as the size of the L/D increased. During the introduction of the cavities the oscillations of pressure was suppressed for higher L/D ratios but the flow remains detached at smaller L/D ratios. R.Jagannath, N.G.Naresh and K.M. Pandey[31] worked on pressure loss in sudden expansion in flow through nozzle: a fuzzy logic approach. In this paper pressure loss in suddenly expanded ducts is studied with the help of fuzzy logic as a tool. It is observed that minimum pressure loss takes place when the length to diameter ratio is one and it is seen that the results given by fuzzy logic formulation are very logical and it can be used for qualitative analysis of fluid flow in flow through nozzles in sudden expansion. To make the problem simpler the linear function is considered throughout the methodology. Moreover, in spite of the flow being supersonic the effects of shock are not being considered. In this paper the main objective is to find the desired L/D ratio for smooth flow development keeping in view all the three parameters like base pressure, wall static pressure and total pressure loss.

III. METHODOLOGY

A. *Logic in Base Pressure:*

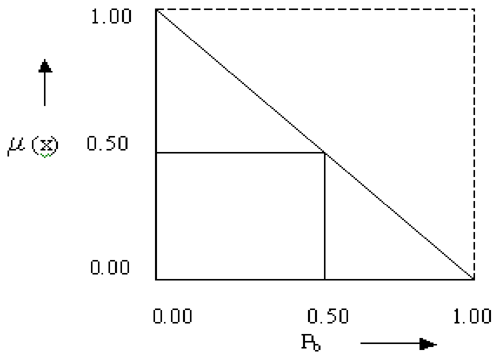

Fig 3.1 Base Pressure membership function

The effect of Base Pressure in the fluid flow is studied from the experiments conducted by K.M. Pandey and E. Rathakrishnan (20). It is inferred from their experiment that, low base pressure is desirable, as the flow tends to remain attached because of low base pressure or low wake. Hence this concept is considered in Fuzzy logic for determining the membership function. As we desire that Base pressure to be low, we assume a membership function μ_x equal to 1 as the lowest possible Base Pressure. As our experimental datas are calculated by considering non-dimensional ratios, i.e. Base Pressure is the ratio of Base pressure and ambient pressure in order to make the quantity dimensionless. The lowest possible Base pressure ratio is 0.00, which can be attained at very high Mach numbers. Hence by considering those criteria into factor the membership function μ_x equal to 1 is assumed for a base pressure ratio of 0.00. Similarly the maximum possible base pressure ratio i.e. base pressure ratio 1 is given a membership function 0 as it is the most undesirable characteristics. Hence this assumption holds true for all the nozzles.

IV. RESULTS AND DISCUSSION

A. *Nozzle with Mach No – 1.58, Pressure Ratio – 2.65 and Area Ratio – 10.00:*

L/D Ratio	**Base Pressure, P_b – M.F**
1	**0.01**
2	**0.07**
4	**0.12**
6	**0.13**

TABLE 1

L/D Ratio	Base Pressure, P_b
1	0.99
2	0.93
4	0.88
6	0.87

TABLE 2

Base Pressure Calculation:
From Table 4.2, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.99, henceforth
M.F = (1-0.99) * (1/1) =0.01.
Rest of the calculations are done as stated in methodology.

B. Nozzle with Mach No – 1.58, Pressure Ratio – 2.65 and Area Ratio – 6.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.02
2	0.13
4	0.23
6	0.24

TABLE 3

L/D Ratio	Base Pressure, P_b
1	0.98
2	0.87
4	0.77
6	0.76

TABLE 4

Base Pressure Calculations:
From Table 4.4, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.98, henceforth
M.F = (1-0.98) * (1/1) =0.02.

C. Nozzle with Mach No – 1.58, Pressure Ratio – 2.65 and Area Ratio – 2.89:

L/D Ratio	Base Pressure, P_b – M.F
1	0.08
2	0.26
4	0.44
6	0.50

TABLE 5

L/D Ratio	Base Pressure, P_b
1	0.92
2	0.74
4	0.56
6	0.50

TABLE6

Base Pressure Calculations:
From Table 4.6, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.92, henceforth
M.F = (1-0.92) * (1/1) =0.08.

D. Nozzle with Mach No – 1.74, Pressure Ratio – 2.65 and Area Ratio – 10.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.00
2	0.04
4	0.13
6	0.13

TABLE 7

L/D Ratio	Base Pressure, P_b
1	1.00
2	0.96
4	0.87
6	0.87

TABLE 8

Base Pressure Calculations:
From Table 4.8, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 1.00, henceforth
M.F = (1-1.00) * (1/1) =0.00.

E. Nozzle with Mach No – 1.74, Pressure Ratio – 2.65 and Area Ratio – 6.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.00
2	0.08
4	0.23
6	0.24

TABLE 9

L/D Ratio	Base Pressure, P_b
1	1.00
2	0.92
4	0.77
6	0.76

TABLE 10

Base Pressure Calculations:
From Table 4.10, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 1.00, henceforth
M.F = (1-1.00) * (1/1) =0.00.

F. Nozzle with Mach No – 1.74, Pressure Ratio – 2.65 and Area Ratio – 2.89:

L/D Ratio	Base Pressure, P_b – M.F
1	0.01
2	0.16
4	0.41
6	0.51

TABLE 11

L/D Ratio	Base Pressure, P_b
1	0.99
2	0.84
4	0.59
6	0.49

TABLE 12

Base Pressure Calculations:
From Table 4.12, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.99, henceforth
M.F = (1-0.99) * (1/1) =0.01.

G. Nozzle with Mach No – 2.06, Pressure Ratio – 2.65 and Area Ratio – 10.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.09
2	0.11
4	0.13
6	0.11

TABLE 13

L/D Ratio	Base Pressure, P_b
1	0.91
2	0.89
4	0.87
6	0.89

TABLE 14

Base Pressure Calculations:
From Table 4.14, the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.91, henceforth
M.F = (1-0.91) * (1/1) =0.09.

H. Nozzle with Mach No – 2.06, Pressure Ratio – 2.65 and Area Ratio – 6.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.08
2	0.03
4	0.21
6	0.20

TABLE 15

L/D Ratio	Base Pressure, P_b
1	0.92
2	0.97
4	0.79
6	0.80

TABLE 16

Base Pressure Calculations:
From Table 4.16 the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.92, henceforth
M.F = (1-0.92) * (1/1) =0.08.

I. Nozzle with Mach No – 2.06, Pressure Ratio – 2.65 and Area Ratio – 2.89:

L/D Ratio	Base Pressure, P_b – M.F
1	0.09
2	0.25
4	0.38
6	0.38

TABLE 17

L/D Ratio	Base Pressure, P_b
1	0.91
2	0.75
4	0.62
6	0.62

TABLE 18

Base Pressure Calculations:
From Table 4.18 the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.91, henceforth
M.F = (1-0.91) * (1/1) =0.09.

J. Nozzle with Mach No – 2.23, Pressure Ratio – 2.65 and Area Ratio – 10.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.01
2	0.04
4	0.09
6	0.09

TABLE 19

L/D Ratio	Base Pressure, P_b
1	0.99
2	0.96
4	0.91
6	0.91

TABLE 20

Base Pressure Calculations:
From Table 4.20 the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.99, henceforth
M.F = (1-0.99) * (1/1) =0.01.

K. Nozzle with Mach No – 2.23, Pressure Ratio – 2.65 and Area Ratio – 6.00:

L/D Ratio	Base Pressure, P_b – M.F
1	0.00
2	0.07
4	0.15
6	0.15

TABLE 21

L/D Ratio	Base Pressure, P_b
1	1.00
2	0.93
4	0.85
6	0.85

TABLE 22

Base Pressure Calculations:
From Table 4.20 the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 1.00, henceforth
M.F = (1-1.00) * (1/1) =0.00.

L. Nozzle with Mach No – 2.23, Pressure Ratio – 2.65 and Area Ratio –2.89:

L/D Ratio	Base Pressure, P_b – M.F
1	0.02
2	0.13
4	0.31
6	0.34

TABLE 23

L/D Ratio	Base Pressure, P_b
1	0.98
2	0.87
4	0.69
6	0.66

TABLE 24

Base Pressure Calculations:
From Table 4.22 the membership function of the base pressure is calculated as given below,
For L/D=1; base pressure is 0.98, henceforth
M.F = (1-0.98) * (1/1) =0.02.

V. CONCLUSION

An optimum L/D ratio is evaluated in the present study using fuzzy-set theory. This objective has already been obtained earlier experimentally. The fuzzy set based methodology could easily consider many attributes concurrently, while deciding the specifications of the suddenly expanded supersonic fluid flow through a straight circular duct. The methodology can be easily extended to a situation involving diverse conflicting objectives. This study can be extended to different nozzles having different geometries with variations in Mach no, pressure ratio and area ratio. It is observed that L/D ratio is 6 for base pressure for Mach 1.58, 1.74, 2.06 and 2.23 , which is in very close agreement with the experimental results cited in the literature.

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REFERENCES

[1] Wick, R.S., 1953, The effect of boundary layer on sonic flow through an abrupt cross sectional area change, *Journal of the Aeronautical Sciences*, Vol. 20, p. 675-682.

[2] Korst, H., 1954, 'Comments on the effect of boundary layer on the sonic flow through an abrupt cross sectional area change', J*ournal. of Aeronautical Sciences,* Vol. 21, p. 568.

[3] Hall, W.B and Orme, E.M., 1955, 'Flow of a compressible fluid through a sudden enlargement in a pipe, P*roceedings of Institution of Mechanical Engineers'*, Vol. 169, p. 007-1022.

[4] Benedict.R.P and Steltz, W.G., 1962, ' A generalized approach to one dimensional gas dynamics', *Trans. ASME (power),* Vol. 84, p. 44.

[5] Zadeh, L.A., 1965, "Fuzzy Sets," Information Control.,Vol. 8. pp. 338-353.

[6] Anderson, J. S and Williams, T. T., 1968, 'Base pressure and noise produced by the abrupt expansion of air in a cylindrical duct', *Journal of Mechanical Engineering Science*, Vol. 10, No. (3), p. 262-268.

[7] Zadeh, L.A., 1973, "Outline of a new approach to the analysis of complex systems and decision Processes", Information Science, Vol. 9, pp.43-80.

[8] Durst.F., Melling, A and Whitelaw, J.J., 1974, ' Low Reynolds number flow over a plane symmetric sudden expansion', *Journal of Fluid mechanics*, Vol. 12, No.6, p.739.

[9] Cherdon, W., Durst, F. and Whitelaw, J.H., 1978, 'Asymmetric flows and instabilities in symmetric ducts with sudden expansions', *Journal of Fluid Mechanics,* Vol. 84, part 1, p.13.

[10] Brady, J.F. and Acrivos, A., 1982, 'Closed cavity laminar flows at a moderate Reynolds numbers', *Journal of Fluid Mechanics,* Vol. 115, p. 427.

[11] Yang, B.T and Yu, M. H., 1983, The flow field in a suddenly enlarged combustion chamber, *AIAA Journal*, Vol. 21, No.1, p. 92-97.

[12] Raghunathan S and Mabey, D. G., 1987, Passive shockwave/boundary-layer control on a wall mounted model, *AIAA Journal*, Vol. 25, No. 2, p. 275-278.

[13] Raghunathan, S., 1987,b Pressure fluctuation measurements with passive shock/boundary layer control, *AIAA journal*, Vol. 25, No. 5, p. 626-628 .

[14] Raghunathan, S., 1987, Effect of porosity strength on passive shockwave/boundary layer control, *AIAA journal,* Vol. 25, No. 5, p. 757-758.

[15] Wilcox, J.F. Jr., 1988, Passive venting system for modifying cavity flow fields at supersonic speeds, *AIAA Journal*, Vol. 26, No. 3, p. 374-376.

[16] Tanner, M., 1988, Base cavities at angles of incidence, *AIAA Journal*, Vol. 26, No. 3, p. 374-377.

[17] Rathakrishnan, E., Ramanaraju, O. V., and Padmanabhan, K., 1989, Influence of cavities on Suddenly expanded flow field, *Mechanics Research communications*, Vol. 16 (3), p. 139-146.

[18] Vishwanath P.R. and Patil, S.R., 1990, 'Effectiveness of passive devices for axi symmetric base drag reduction at Mach 2', *Journal of Spacecraft,* p. 234, (May-June).

[19] Kruiswyk, R.W and Dutton. J. C., 1990, 'Effect of base cavity on subsonic near wake flow', *AIAA Journal*, Vol. 28, No. 11, p.1885-1895.

[20] Pandey,K.M., 1994, Studies on flow through nozzles with sudden expansion, Ph.D. thesis, Department of Mechanical Engineering, IIT Kanpur.

[21] Pandey K M, 1995, Studies on flow through nozzles in sudden expansion with passive control, International conference at IISc, Bangalore on recent advances in Mechanical Engineering, Dec 20-22, pp 1511-1518, Narosa publications, New Delhi, India, 1995, Volume 2 .

[22] Pandey K M, 1996, Base flow in flow though nozzles with sudden expansion: a study in supersonic regime-2nd National Conference on Fluid Machinery, Dept of Mechanical Engg, PSG College of Technology, Coimbatore, India, June 28-29, pp 256-265, Allied publishers Ltd. New Delhi, India.

[23] Pandey K M, 1997, Pressure loss in flow through nozzles with sudden expansion: a comparison between supersonic and subsonic flow regime, International Conference on Advances in Mechanical and Industrial Engg, Dept of Mechanical and Industrial Engg., Roorkee, India, Feb 6-8, pp 417-426, Ajay printers and publishers, Roorkee, India, Volume 2 .

[24] Pandey K M , S A Khan and Rathakrishnan E, 2000, Passive control of base flows, Proceedings of the National Seminar on Recent Advances in Experimental Mechanics, Dept of Aerospace Engg, IIT Kanpur, Mar 15-16, , Allied Publications Ltd, New Delhi, India 2000 PP-57-71.

[25] Dixit, U.S., Dixit, P.M., 2000, 'Application of fuzzy set theory in the scheduling of a Tandem cold-Rolling Mill', *ASME*, Vol. 122, p. 494-500.

[26] Rathakrishnan E., 2001, 'Effect of ribs on suddenly expanded flows', *AIAA Journal*, Vol. 39, No. 7, p.1402-1404 .

[27] Dixit, U.S., Robi, P.S., Sarma, D.K., 2002, 'A systematic procedure for the design of a cold rolling mill', *Material Processing Technology* , Vol. 121, p. 69- 76 .

[28] Abburi, N.R., Dixit, U.S., 2006, 'A knowledge-based system for the prediction of surface roughness in turning process', *Robotics and Computer-Integrated manufacturing,* Vol. 22, p. 363- 372 .

[29] Pandey, K.M., and Rathakrishnan E., 2006, 'Influence of cavities on flow development in sudden expansion', *International Journal of Turbo and Jet Engines,* Vol. 23, p. 97- 112.

[30] Pandey, K.M., and Rathakrishnan E, 2006, 'Annular cavities for Base flow control', *International Journal of Turbo and Jet Engines,* Vol. 23, p. 113- 127.

[31] R. Jagannath, N.G.Naresh and K.M.Pandey, 2007 'Studies on Pressure loss in sudden expansion in flow through nozzles: A Fuzzy Logic Approach', *ARPN Journal of Engineering and Applied Sciences,* Vol 2, No.2, p. 50 –61, April.

Dr. K.M.Pandey did his PhD in Mechanical Engineering in 1994 from IIT Kanpur. He has published and presented 150 papers in International & National Conferences and Journals. Currently he is working as Professor of the Mechanical .Engg Department, National Institute of Technology, Silchar, Assam, India..He also served the department in the capacity of head from July 07 to June 2010. He has also worked as faculty consultant in Colombo Plan Staff College, Manila, Philippines as seconded faculty from Government of India. His research interest areas are the following; Combustion, High speed flows, Technical Education, fuzzy logic and neural network , heat transfer, internal combustion engines, human resource management, gas dynamics and numerical simulations in CFD from commercial software. K.M.Pandey(email: kmpandey2001@yahoo.com)