Wall Static Pressure Variation In Sudden Expansion In Flow Through De Laval Nozzles At Mach 1.74 And 2.23 In Circular Ducts Without Cavities: A Fuzzy Logic Approach

K.M.Pandey, Jagannath Rajshekharan and Sukanta Roga

***Abstract*— In this paper the analysis of wall static pressure variation has been done with fuzzy logic approach to have smooth flow in the duct. Here there are three area ratio choosen for the enlarged duct, 2.89, 6.00 and 10.00. The primary pressure ratio is taken as 2.65 and cavity aspect ratio is taken as 1 and 2. The study is analysed for length to diameter ratio of 1,2,4 and 6. The nozzles used are De Laval type and with a Mach number of 1.74 and 2.23. The analysis based on fuzzy logic theory indicates that the length to diameter ratio of 1 is sufficient for smooth flow development if only the basis of wall static pressure variations is considered. Although these results are not consistent with the earlier findings but this opens another method through which one can analyse this flow. This result can be attributed to the fact that the flow coming out from these nozzles are parallel one.**

***Index Terms*— wall static pressure, area ratio, pressure ratio, De Laval nozzle, Mach number.**

NOTATION

Ar 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.

Pa Ambient atmospheric pressure.

P01 Stagnation pressure in the settling chamber , also called primary pressure.

L Length of enlarged duct.

M Mach number at the nozzles exit.

ST Represents enlarged duct without cavities.

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I. INTRODUCTION

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 [30]. 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 [31]. 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.

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A. *FUZZY SET THEORY*

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

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

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.

B. *LITERATURE REVIEW*

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 [5] 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. [6] 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. [7] studied symmetric 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. [6] 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 amplifies 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 [8] 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 [9]. The combustion chamber consisted of circular Plexiglas with a suddenly enlarged section followed by a nozzle. The Reynolds number based o 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.

Rathakrishnan et al. [10] 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. Raghunathan and Mabey [11] 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 [12] studied pressure fluctuation with positive shock position showed an appreciable decrease in drag compared with solid surface model. Raghunathan [13] 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. [14] studied the passive venture 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 [15] 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.

The effectiveness of a passive device for axi-symmetric base drag reduction at Mach 2 was studied by vishwanath and patil [16]. 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. Kruiswtk and Dutton [17] 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.

Rathakrishnan [18] demonstrated that a control in the form of annular ribs can 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. Pandey, K.M, and Rathakrishnan E. [19] 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.

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. Air flow 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. [21]. 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 no. the base pressure was found to be smooth and without oscillation in the mach no range of 0.6- 1.0.

Flow from nozzles expanding suddenly into circular pipes with and without annular cavities was experimentally investigated by Pandey, K.M., [22] for mach no range of 1.00 – 2.75. The base pressure was found increasing with increasing mach no's as expected for supersonic Mach numbers. The effect of aspect ratio on base pressure is only marginal for supersonic mach no'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 no 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 no, 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.

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. [24], for mach no 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.

Abburi and Dixit [25] 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. Dixit and Dixit [26] 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, inter stand tensions, roll speed, roll 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. 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.To make the problem simpler the linear function is considered throughout the methodology. We were provided with datas, which were collected from the experiment conducted by Dr. K.M. Pandey at I.I.T. Kanpur. Moreover, in spite of the flow being supersonic the effects of shock are not being considered.

II. MATERIALS AND METHODS

A. Logic in Wall Static Pressure

The effect of Wall Static Pressure in the fluid flow is studied from the experiments conducted by K.M. Pandey and E. Rathakrishnan in 1991 at IIT Kanpur. The datas are taken from Ph. D thesis(-). It is obvious that, low pressure variation is desirable, as to attain smooth flow. Hence this concept is considered in Fuzzy logic for determining the membership function. As we desire that wall static pressure variation to be low, we assume a membership function 1 to the lowest possible wall static Pressure variation. The lowest possible wall static pressure variation is 0.00. Hence by considering those criteria into factor the membership function 1 is assumed for a wall static pressure variation of 0.00. Similarly the maximum possible wall static pressure variation i.e. as per experimental data's the corresponding maximum wall static pressure variation for a particular nozzle and irrespective of the area ratio factor, the membership function is assumed 0. The similar fashion as in base pressure is not being processed, because it is difficult to calculate theoretically the maximum possible wall static pressure variation.

The sense of ignoring the area ratio was for this reason that the final value is optimized as which area ratio proves the best for the particular nozzle. As the maximum pressure loss shall vary nozzle to nozzle, there are four possible assumptions that are to be made for deciding their corresponding membership functions.

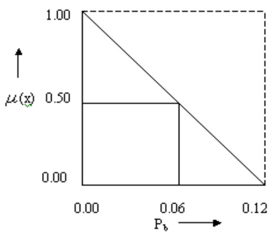

Fig 3.1 Wall Static Pressure Variation M.F For Nozzle with mach no - 1.58

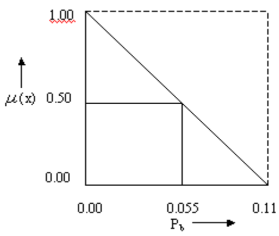

Fig 3.2 Wall Static Pressure Variation M.F For Nozzle with mach no - 1.74

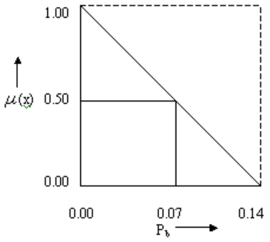

Fig 3.3 Wall Static Pressure Variation M.F For Nozzle with mach no - 2.06

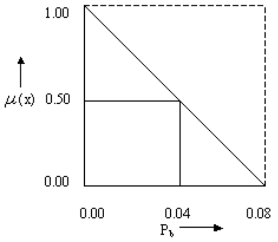

Fig 3.4 Wall Static Pressure Variation M.F For Nozzle with mach no - 2.23

III. RESULTS AND DISCUSSION

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.92
2	0.83
4	0.75
6	0.75

Table A1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.01
2	0.02
4	0.03
6	0.03

Table A2

Wall Static Pressure calculations:

From Table A2, for L/D=1, the membership function for the Wall Static Pressure variation of 0.01 is calculated as, M.F = (0.12-0.01) * (1/0.12) =0.92. Here L/D = 1 is needed for smooth flow development.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.92
2	0.67
4	0.67
6	0.42

Table B1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.01
2	0.04
4	0.04
6	0.07

Table B2

Wall Static Pressure Calculation:

From Table B2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.01 is calculated as, M.F = (0.12-0.01) * (1/0.12) =0.92. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.75
2	0.17
4	0.00
6	0.08

Table C1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.03
2	0.10
4	0.12
6	0.11

Table C2

Wall Static Pressure Calculation:

From Table C2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.03 is calculated as, M.F = (0.12-0.03) * (1/0.12) =0.75. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	1.00
2	0.91
4	0.55
6	0.55

Table D1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.00
2	0.01
4	0.05
6	0.05

Table D2

Wall Static Pressure Calculation:

From Table D2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.00 is calculated as M.F = (0.11-0.00) * (1/0.11) =1.00. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.82
2	0.64
4	0.55
6	0.27

Table E1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.02
2	0.04
4	0.05
6	0.08

Table E2

Wall Static Pressure Calculation:

From Table E2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.02 is calculated as M.F = (0.11-0.02) * (1/0.11) =0.82. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.91
2	0.64
4	0.00
6	0.09

Table F1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.01
2	0.04
4	0.11
6	0.10

Table F2

Wall Static Pressure Calculation:

From Table F2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.01 is calculated M.F = (0.11-0.01) * (1/0.11) =0.91. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.57
2	0.71
4	0.86
6	0.86

Table G1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.06
2	0.04
4	0.02
6	0.02

Table G2

Wall Static Pressure Calculation:

From Table G2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.06 is calculated as M.F = (0.14-0.06) * (1/0.14) =0.57. The rest of the calculations are self-explanatory. In this case it is observed that for L/D = 4 as well as L/D = 6 possess highest membership function, so this is needed for smooth flow development. The nozzle used here is a conical nozzle and flow is coming in the duct with an angle of 5 degrees.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.86
2	0.71
4	0.21
6	0.57

Table H1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.02
2	0.04
4	0.11
6	0.06

Table H2

Wall Static Pressure Calculation:

From Table H2, For L/D=1; the membership function of the Wall Static Pressure variation of 0.02 is calculated M.F = (0.14-0.02) * (1/0.14) =0.86. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.71
2	0.36
4	0.14
6	0.00

Table I1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.04
2	0.09
4	0.12
6	0.14

Table I2

Wall Static Pressure Calculation:

From Table I2, Ffr L/D=1; the membership function of the Wall Static Pressure variation of 0.04 is calculated as M.F = (0.14-0.04) * (1/0.14) =0.71. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	0.88
2	0.88
4	0.63
6	0.63

Table J1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.01
2	0.01
4	0.03
6	0.03

Table J2

Wall Static Pressure Calculation:

From Table J2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.01 is calculated as M.F = (0.08-0.01) * (1/0.08) =0.88. Here L/D = 1 as well as L/D = 2 is needed fpr smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	1.00
2	0.75
4	0.38
6	0.25

Table K1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.00
2	0.02
4	0.05
6	0.06

Table K2

Wall Static Pressure Calculation:

From Table K2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.00 is calculated as M.F = (0.08-0.00) * (1/0.08) =1.00. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

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

L/D Ratio	Wall Static Pressure, P_w-M.F
1	1.00
2	0.50
4	0.00
6	0.00

Table L1

L/D Ratio	Wall Static Pressure, Pw_x-$Pw_{(x+1)}$
1	0.00
2	0.04
4	0.08
6	0.08

Table L2

Wall Static Pressure Calculations:

From Table L2, for L/D=1; the membership function of the Wall Static Pressure variation of 0.00 is calculated M.F = (0.08-0.00) * (1/0.08) =1.00. Here L/D = 1 is needed for smooth flow development. The rest of the calculations are self-explanatory.

IV. 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 1 for wall static pressure variation for Mach No 1.58, 1.74, 2.06 and 2.23.

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