Low-Cost Base Drag Reduction Technique

Mohammed Asadullah*, Sher Afghan Khan, Waqar Asrar, Sulaeman.E
Department of Mechanical Engineering, International Islamic University Malaysia
Email: shiblibhai@gmail.com, {sakhan, waqar, esulaeman}@iium.edu.my

***Abstract*—A simple, low-cost, drag reduction device has been developed for applications in high-speed flows. This low-cost technology is expected to decrease fuel consumption (e.g., for high-speed vehicles such as rockets traveling from a highly overexpanded flow at the sea level to a highly underexpanded flow in outer space). Somewhere in between the over and the underexpansion, the rocket experiences perfectly expanded flows. In this study, only overexpanded and perfectly expanded flows have been considered. A single cylinder with a diameter of 2 mm is rotated clockwise inside the recirculation zone (e.g., in high-speed vehicles) to act as a controller. The base pressure in the dead zone and the wall pressure along the square duct length have been measured with and without control. Experiments were carried out for nozzle pressure ratios (NPRs) of 2, 3, 6 and 7.8. When the cylinder was rotated clockwise as an active controller, the base pressure was found to increase by as much as 56% in the perfectly expanded case and up to 17% in overexpanded flows. This drastic increase in the base pressure is correlated to an equivalent drag reduction. In addition, adding an active control had no negative impact on the main flow field. This is important as any disturbance in the main flow field at high speeds may lead to increased oscillations and vibrations, which if not checked may cause material failures. Rotating the cylinder in the clockwise direction near the wall was found to be very effective for higher NPRs.**

***Index Terms*—nozzle pressure ratio, Mach number, base pressure, wall pressure, active control.**

I. Introduction

In gas dynamics related to the interaction of supersonic jets, the flow of supersonic jets with a sudden expansion is a problem in many engineering applications [1]. Further sudden expansion leads to flow separation, recirculation, and reattachment and has many engineering applications [2]. In high-speed vehicles, such as ballistic missiles, projectiles, and rockets, the depression at the base in the jet-off condition amounts to a base drag as high as 50% of the total drag [3]. Previously, researchers have developed several methodologies and tools to actively control the flow field [4]. Active control techniques need input energy, which makes them a bit expensive, but can be very effective [5], such as periodic suction and injection [6], microjets [7], and plasma actuators [8], which are being studied by few researchers. In addition, drag reduction and damping dangerous vibrations are equally important in high-speed vehicles at different regimes [9]. Pressure drag consists of wave drag and base drag. In the present study, we will investigate the base drag. To manage the flow control in a desired manner, a control device is needed. Herein, we propose a cylinder rotating in the clockwise direction when viewed from the top to modify the base pressure as per the requirements.

II. Literature Review

High-speed compressible flow regimes have high pressure shock waves and a very-low-pressure recirculation zone. This leads to high wave and base drag. Thus, a control device that can modify the flow pattern inside the recirculation zone in a desired manner is needed. Here, we proposed a rotating cylinder to use as a controller. To our knowledge, this is being studied for the first time in high-speed compressible flow regimes. The cylinder itself is a bluff body that has an inherent vortex shedding behind it. The problem of flow past a rotating cylinder at a low Reynolds (Re) number was studied extensively in [10], but the author only concentrated on the lift due to the Magnus effect and boundary layer control on an aerofoil. Changes in the velocity profile were studied near the top and bottom due to the effect of spinning cylinder on the flow fieldin [11]. A detailed investigation of two circular stationary cylinders in various arrangements was made and their physics were somewhat understood, but the cylinders were not studied in the recirculation zone or for the reduction of the base drag [12]. An experimental study of vortex-induced vibration in the crossflow direction of a rotating circular cylinder was carried out in [13]. Suppressing the vortex shedding of a cylinder at low Re numbers was achieved using a smaller cylinder outside the recirculation area in the wake of the main cylinder for incompressible flows [14]. Mittal et al. studied the stability analysis of flow past a circular cylinder [15]. They concluded that a very high lift coefficient can be achieved for high rotational rates of cylinders, but at a critical rotation, instability is unavoidable. Stojkovic et al. studied the effect of high rotation rates on the laminar flow around a circular cylinder, for higher Re in the steady flow regime [16]. They concluded that the inherent drag force of the cylinder decreases with increasing rotational velocities. From a review of the cylinder study, the flow physics are well supported by a vast amount of literature. Most of the focus was on incompressible low-speed flows and on reducing the vortex shedding behind the cylinder by reducing its diameter and/or rotating it, but there is no single case to the authors' knowledge in which the

Manuscript received January 6, 2018; revised June 1, 2018

doi: 10.18178/ijmerr.7.4.428-432

cylinder was used to control the base drag in compressible flows for high-speed flows. We propose using a clockwise rotating cylinder as an active controller.

III. Experimental Setup and Procedure

A. Supersonic Speed Facility

The experiments were conducted at the BIT Research Centre at the supersonic laboratory, Mangalore, Karnataka, India. The supersonic speed facility consists of a settling chamber, with a provision to mount the jet nozzle on its flange. Compressed dry air is stored at a pressure of 300 psi in the storage tank, as shown in Fig. 1.

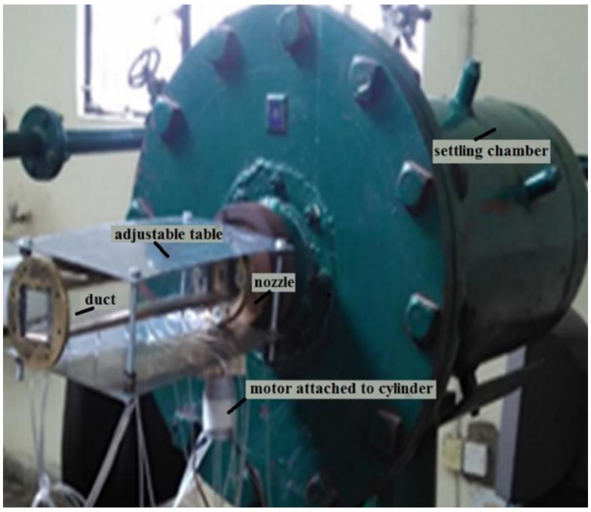


Figure 1. Photographic view of the experimental setup.

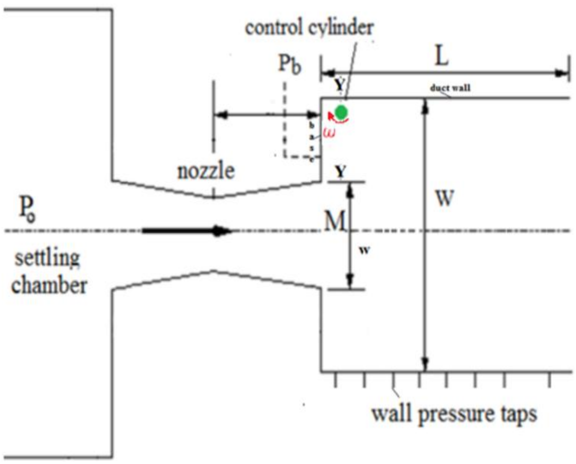


Figure 2. A schematic drawing of the nozzle and the duct.

Compressed air from the storage tank is supplied to the settling chamber at a high pressure of 150 psi through a pressure regulatory valve (PRV), as shown in Fig. 2.

Once the flow attains equilibrium in the settling chamber, it is expanded through the square nozzle to the suddenly expanded square duct. The desired stagnation pressure at the settling chamber is achieved by controlling the PRV. The Pressure Transducer 9205 is used for measuring the base pressure behind the exit of the nozzle, the wall pressure along the duct, and the stagnation pressure in the settling chamber. It has 16 channels and its pressure range is approximately 0–150 psi. It averages 250 samples per second and displays the reading. The user-friendly menu driven LabVIEW software along with data acquisition (DAQ) acquires the data and displays the readings from all the channels simultaneously on a computer screen.

B. Fabrication Process

The supersonic nozzle fabricated from brass, used in the present study, is for Mach 2. The exit area of the square nozzle is $100 mm^2$. The control cylinder with a 2 mm diameter is shown as a green dot in Fig. 2. It is attached to the motor for rotation and is positioned at 8 mm from the nozzle exit and at 2 mm from the side wall. The base pressure was measured at four places by nozzle ports at 11.5 mm from the center. The flange of the square nozzle has eight holes to fasten it with the square duct. A sudden expansion square duct was also fabricated from brass, with its length 10 times its width (i.e., L/W = 10). Pressure taps along the duct wall of 1 mm internal diameter steel tubes were used to record the wall pressure. Taps begin at 7 mm from the nozzle exit. Initially, these were 3 mm apart and the distance between them in the axial direction progressively increased until the maximum duct length of 290 mm. The nozzle pressure ratios (NPRs) used in this study were 2, 3, 6, and 7.8. The area ratio A_2/A_1 and the length-to-width ratio (L/W) were 9 and 10 for all the NPRs. Measurements were made for all NPRs with and without a control. Measurements for all NPRs with and without a control were completed for a square duct of with a cross-sectional area of 30 × 30. The base pressure and wall pressure were made nondimensional with atmospheric pressure and were presented as P_b/P_a and P_w/P_a after converting all readings from the gage pressure to absolute pressure.

IV. Results and Discussion

The main objective of this investigation is to ascertain the effectiveness of the active control in the form of a clockwise rotating cylinder, located in the recirculation zone, to control the base pressure. The parameters considered are NPR, L/W, and A_2/A_1 at Mach 2. To observe the increase and its effectiveness in the base pressure at different NPRs with and without control, the base pressure results are also presented in percentages. The percentage change in the base pressure is given by

$$P_b = [(P_{b\ control} - P_{b\ no\ control})/P_{b\ no\ control}] \times 100.$$

Fig. 3 presents the percentage change in the base pressure for various NPRs. From the results, it is evident that if the flow remains overexpanded, the control effectiveness will be marginal, and this trend continues until the NPR approaches the NPR required for flow to become perfectly expanded at the nozzle. At NPR = 2, the supersonic flow from the nozzle is highly overexpanded, and hence there is nearly a 3% increase in the base pressure when the location of the cylinder was fixed at 2 mm from the duct wall and control in the form of a dynamic cylinder rotating clockwise, whereas at NPR = 3, the gain in the base pressure is nearly 7%. At NPR = 6, the percentage increase in the base pressure is 17%. The physics behind this increase in the base pressure seem to be due to its location in the base corner being close to the wall, the area ratio of the duct, and clockwise direction of rotation of the control cylinder against the vortex, its interaction with the nozzle shear layer, the dividing stream line at the nozzle exit, and the boundary layer interactions. The NPRs tested are such that the flow from the nozzle is overexpanded (NPR = 2 to 6) and perfectly expanded (NPR = 7.8). From Figs. 3 and 4, it is seen that if the flow is overexpanded, the effectiveness of the active control in the form of the rotating cylinder is only marginal and the percentage increase in the base pressure remains in the range from 3 to 17% for these NPRs. However, when the tests were conducted for NPR = 7.8, there was a substantial increase in the base pressure (56%). Hence, when the aim is to increase the base pressure and decrease the base drag, then NPR = 7.8 is the right choice. In the case of unguided rockets, missiles and canon launched shells where the base drag is 50% of the total drag at low supersonic Mach numbers, will be very useful to increase the range of the weapon system.

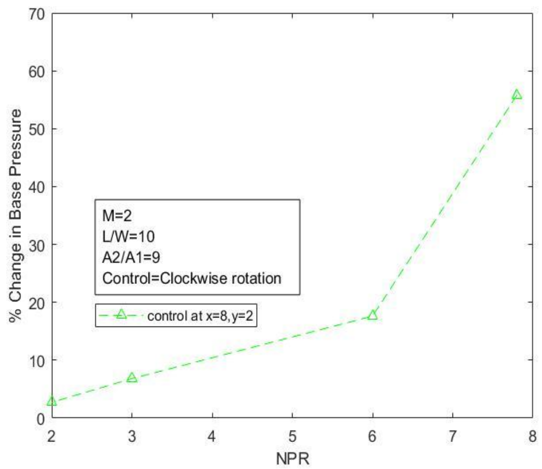


Figure 3. Percentage change in P_b with NPR.

The variation of the base pressure with the NPR is shown in Fig. 4. For the case without control, the base pressure continues to decrease for all the NPRs. The reason for this trend is that the area ratio is very high, which means that the flow has got sufficient relief, and the vortex located in the base region will not be able to create suction, which will be possible in the case of lower area ratios. Hence, with the increase in the NPRs, the overexpansion level will decrease continuously, and the same is observed in Fig. 4. When the active control as a clockwise rotating cylinder was employed, it was observed that, right from NPR = 2 to 6, the base pressure increased, keeping the trend of base pressure decreasing till NPR = 6, and then it started increasing substantially from NPR = 7.8.

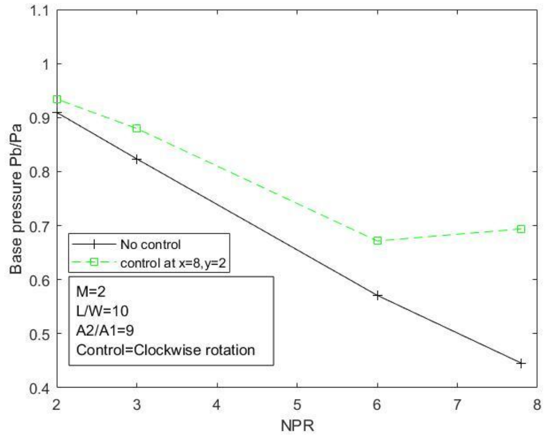


Figure 4. Base percentage variation with NPRs.

This appreciable increase happens when the jets are correctly expanded. This trend matches the existing benchmark [17]. As the control cylinder is itself a bluff body and has an inherent property of shedding vortices, there is a possibility that it might disturb the flow field in the square duct. To observe the nature of the flow field in the duct, the wall pressure was measured. Wall pressure distributions along the longitudinal axis of the duct for NPR = 2 and 3 are shown in Figs. 5 and 6.

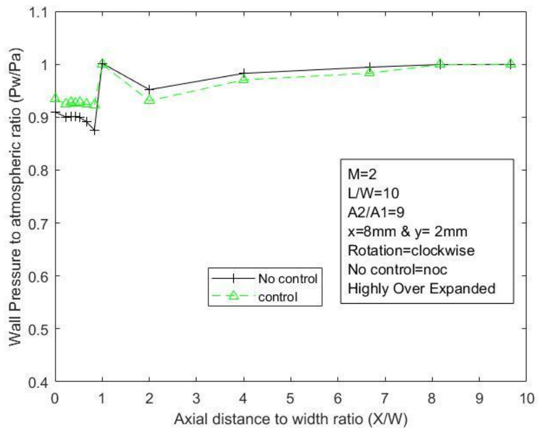


Figure 5. Flow development in the duct at NPR = 2.

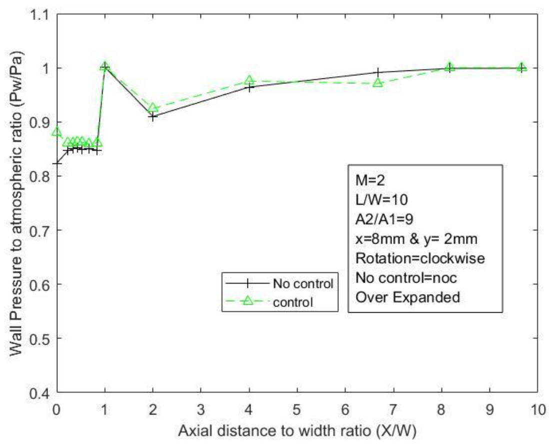


Figure 6. Flow development in the duct at NPR = 3.

A critical condition is reached at NPR = 1.89, leading to overexpansion at the nozzle exit at NPR = 2. The wall pressure in the enlarged duct begins with a very high value of 0.94, decreasing up to X/W = 1 without control, which seems to be the reattachment length, and then further downstream, due to the presence of a shock wave, it shoots out to atmospheric pressure measured equal to atmospheric pressure. Again, a drop in pressure is observed at X/W = 2 due to the presence of an expansion fan, and then further downstream it reached atmospheric pressure. In the base region, there is a variation of the base pressure in the range of 3–8% for NPR = 2 and 3. Interestingly, there was no adverse effect due to the active control, as evident from the wall pressure flow field, which is a very good phenomenon whenever control is employed (Figs. 5 and 6). Figure 7 shows the wall pressure for NPR = 6. At X/W = 1, the shock strength was very strong as the wall pressure jumped from 0.65 to 1.0, which is almost the ambient pressure value. Further, control is very effective at this NPR and results in a considerable increase in the wall pressure for X/W in the range from 2 to 6, and later downstream there is a nominal increase of the wall pressure along the length of the enlarged duct. Once, however, at NPR = 6, in the absence of control, the flow field shows a steep and sharp exit to atmospheric pressure, but when control is activated, the wall pressure accommodates within the reattachment length and then recovery takes place smoothly till the end of the duct.

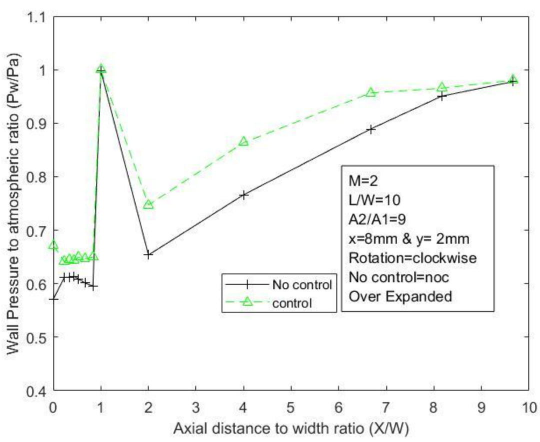


Figure 7. Flow development in the duct at NPR = 6.

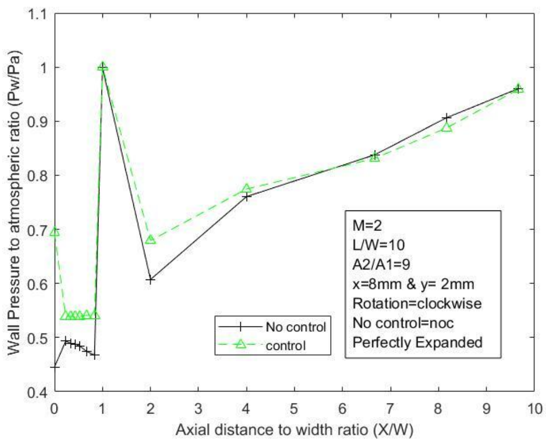


Figure 8. Flow development in the duct at NPR = 7.8.

Clearly, the effectiveness of the control cylinder can be seen at X/W = 0, where before control the pressure was quite low, but when the control was employed, the base pressure got enhanced by 56%, unlike in the previous case. Even though the nozzle is perfectly expanded as seen in Fig. 8, we observe the sudden increase as well as the decrease in the wall pressure at X/W = 1 and 2, which shows that the shock waves are present in the flow field of the duct. When we see the wall pressure results for correct expansion at NPR = 7.8, within the reattachment length, the strong shock wave exists and control results in a decrease as well as a marginal increase in the wall pressure. Control reversal is seen at X/W = 6. The results for correct expansion have different trends in comparison to the results at lower NPRs, namely, 2, 3, and 6, where jets are overexpanded. In the presence of an oblique shock, the flow will deflect away from the base, and in this situation, when a control is employed, it will entrain some mass from the dead region toward the downstream. Apart from this, there will be an interaction among the boundary layer, the free shear layer, and the base vortex.

V. Conclusions

The base drag is dependent on the flow parameters, such as the NPR and the Mach number (M), and on the geometric parameters, such as the area ratio (A_2/A_1) and length-to-width ratio (L/W). When a control was deployed as a rotating cylinder in the clockwise direction against the base vortex with its position fixed at 2 mm from the wall, the higher NPR seemed to be the best option. The control effectiveness is enhanced with the decrease in the level of overexpansion. When the flow is overexpanded at lower NPRs, the control effectiveness is marginal until NPR = 6, which shows that the base pressure is strongly dependent on the level of expansion. When the nozzles are perfectly expanded, the base pressure assumes lower values unlike in the case of overexpansion, where due to the presence of an oblique shock at the nozzle exit, the base pressure values were very high and the control was effective. The flow field in the duct remains identical until the perfectly expanded case, but it shows some fluctuations in the flow field after X/W = 4. The active control cylinder, when rotated against the vortex, seems to be effective for higher NPRs (NPR > 6). The flow field for a perfectly expanded nozzle is dominated by wave drag.

Acknowledgment

The authors wish to acknowledge and thank Bearys Institute of Technology, Mangalore, India, for allowing them to utilize the research facilities at the supersonic laboratory.

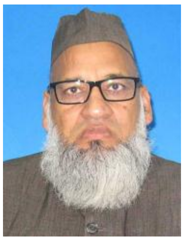
References

[1] N. V. Prodan, "History of base pressure experimental research," *Life Science Journal*, vol. 11, 2014.

[2] A. S. Kherbeet, H. Mohammed, K. Munisamy, and B. Salman, "The effect of step height of microscale backward-facing step on mixed convection nanofluid flow and heat transfer

characteristics," *International Journal of Heat and Mass Transfer,* vol. 68, pp. 554-566, 2014.
[3] P. Viswanath, "Flow management techniques for base and afterbody drag reduction," *Progress in Aerospace Sciences,* vol. 32, pp. 79-129, 1996.
[4] M. Gad-el-Hak, *Flow Control: Passive, Active, and Reactive Flow Management. 2000,* ed: Cambridge University Press.
[5] J. F. Beaudoin, O. Cadot, J. L. Aider, and J. E. Wesfreid, "Drag reduction of a bluff body using adaptive control methods," *Physics of Fluids,* vol. 18, p. 085107, 2006.
[6] D. Williams and C. Amato, "Unsteady pulsing of cylinder wakes," in *Frontiers in experimental fluid mechanics*, ed: Springer, 1989, pp. 337-364.
[7] S. A. Khan and E. Rathakrishnan, "Control of suddenly expanded flows with micro-jets," *International Journal of Turbo and Jet Engines,* vol. 20, pp. 63-82, 2003.
[8] M. Kühn, M. Kühn-Kauffeldt, J. Schein, and A. Belinger, "Plasma actuators for active flow control based on a glow discharge," *Journal of Physics: Conference Series*, 2017, p. 012007.
[9] D. Saile, A. Gülhan, and A. Henckels, "Investigations on the near-wake region of a generic space launcher geometry," in *17th AIAA International Space Planes and Hypersonic Systems and* Technologies *Conference, Manuscript ID*, 2011.
[10] H. Badr, S. Dennis, and P. Young, "Steady and unsteady flow past a rotating circular cylinder at low Reynolds numbers," *Computers & Fluids*, vol. 17, pp. 579-609, 1989.
[11] F. Díaz, J. Gavaldà, J. Kawall, J. Keffer, and F. Giralt, "Vortex shedding from a spinning cylinder," *The Physics of fluids,* vol. 26, pp. 3454-3460, 1983.
[12] M. Zdravkovich, "Review of flow interference between two circular cylinders in various arrangements," *Journal of Fluids Engineering,* vol. 99, pp. 618-633, 1977.
[13] B. Seyed-Aghazadeh and Y. Modarres-Sadeghi, "An experimental investigation of vortex-induced vibration of a rotating circular cylinder in the crossflow direction," *Physics of Fluids,* vol. 27, p. 067101, 2015.
[14] P. Strykowski and K. Sreenivasan, "On the formation and suppression of vortex 'shedding'at low Reynolds numbers," *Journal of Fluid Mechanics,* vol. 218, pp. 71-107, 1990.
[15] S. Mittal and B. Kumar, "Flow past a rotating cylinder," *Journal of Fluid Mechanics,* vol. 476, pp. 303-334, 2003.
[16] D. Stojković, M. Breuer, and F. Durst, "Effect of high rotation rates on the laminar flow around a circular cylinder," *Physics of Fluids,* vol. 14, pp. 3160-3178, 2002.
[17] M. Samimy, K. Zaman, and M. Reeder, "Effect of tabs on the flow and noise field of an axisymmetric jet," *AIAA Journal,* vol. 31, pp. 609-619, 1993.

Asadullah Mohammed is pursuing his Ph.D. degree and is an Assistant Teacher at the Department of Mechanical Engineering, International Islamic University Malaysia. His area of research is high-speed flows, fluid dynamics, experimental aerodynamics, and flight dynamics.



Sher Afghan Khan is a Professor at the Department of Mechanical Engineering, International Islamic University Malaysia. He holds a Ph.D. degree in engineering. His interest is in active and passive control of high-speed jets, sudden expansion problems, drag reduction techniques, stability derivatives for delta wings, ogives, and so forth in supersonic and hypersonic flow.

Waqar Asrar is a Professor at the Department of Mechanical Engineering, International Islamic University Malaysia. He holds a Ph.D. degree in engineering. His research and teaching experience is in space mission analysis, space propulsion, electric propulsion, plasma, simulations, finite element analysis, computational fluid dynamics, and thermal systems.

Sulaeman Ervin is a Professor at the Department of Mechanical Engineering, International Islamic University Malaysia. He holds a Ph.D. degree in engineering. His research interest includes aeroelasticity, applied and computational mathematics, computational fluid dynamics, and finite element analysis.

.