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Investigation of Base Pressure Variations in Internal and External Suddenly Expanded Flows using CFD analysis

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ABSTRACT

The Aerodynamic base drag because of negative pressure at the backward-facing step is a general obstacle connected with all the moving projectiles. The aerodynamic base drag is undesirable since its contribution to the cumulative drag is substantial. The study of pressure variations in the base region is of immense help for all moving projectiles. The experimental study of aerodynamic drag over missile/projectile in a wind tunnel has various disadvantages like a considerable amount of air supply is required to conduct the test, the support mechanism is required to hold the model in wind tunnel test section which creates disturbance in the flow field and introduce the errors in the measurements. In this research paper, the similarities of base pressure variations in internal and external flows are studied using computational fluid dynamics (CFD) analysis. The CFD analysis is carried out at Mach numbers from 0.1 to 3.0. From the results, it has been found that the flow field in the base region of internal and external suddenly expanded flows are nearly the same. The base pressure in external flow can be studied relatively easily by considering it as an internal flow for Mach numbers in the range of 0.1 to 0.4 and 1.4 to 3.0, except when the Mach number is close to unity.

1. Introduction

Aerodynamic drag is one of the principal obstructions to accelerate a solid body traveling in the air. When a vehicle consumes fuel to accelerate, the drag pulls it back to decelerate. Thus, the fuel efficiency is affected adversely. The aerodynamic drag on-highway vehicles, racing cars, and other road vehicles are responsible for a considerable portion of the vehicle's fuel consumption, and from 50% to 60% of total fuel are consumed to overcome the drag force [1-2].

The base drag in any moving projectile is present due to the sub-atmospheric at the blunt base of the projectile. In the external flow over any projectile, the flow is suddenly expanded at the rear end which results in low pressure at the blunt base of the projectile as shown in Figure 1. The similar

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type of phenomenon exists, when the flow is suddenly expanded in the base region of an enlarged duct as shown in Figure 2.

The study of the base drag of a projectile/missile can be studied easily by studying the base drag in the base region of a suddenly expanded duct. Hoerner [3] concluded that the mechanism of internal and external flow is nearly the same and the base pressure occurrence in external flow can be studied relatively easily by experiments with an internal flow. The advantages of experimentation of internal flow over external flow are the reduction in the air supply, support mechanisms are eliminated, and the base pressure can be measured easily in the wake region.

In the literature, several authors have studied the effectiveness of microjets experimentally to increase base pressure in the recirculation zone of the square duct [4-13, 22-33]. Asadullah *et al.,* [14-17] have worked on a passive method and an active method to control the base pressure by the static and dynamic cylinders. Pathan *et al.,* [18-20] have studied the parameters affecting suddenly expanded flows. Pathan *et al.,* [21] have optimized the area ratio of an enlarged duct to produce maximum thrust form a converging-diverging nozzle.

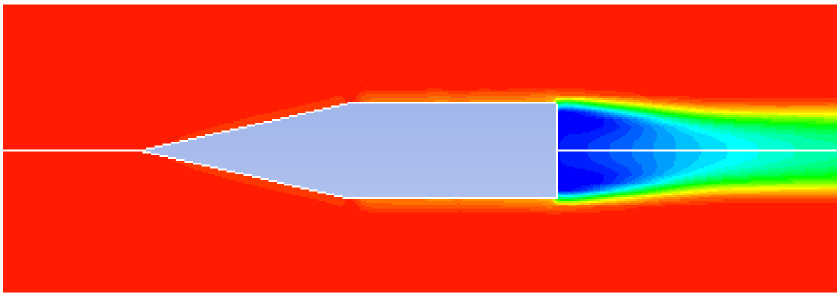


Fig. 1. The base pressure variations in external flow over a body

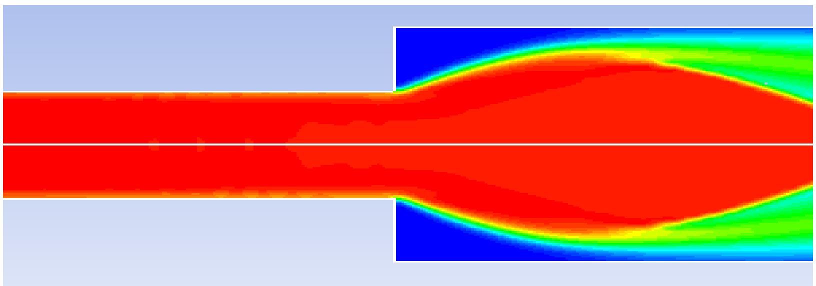


Fig. 2. The base pressure variations in internal flow with a suddenly expanded duct

In the literature, many authors have worked on the control of base pressure in internal as well as external suddenly expanded flows. In the literature, the similarities between the internal and external suddenly expanded flows are not available. In this research paper, the similarities of base pressure variations in internal and external suddenly expanded flows have been analyzed using CFD analysis.

2. Methodology

2.1 CFD Analysis

Various geometries for external and internal flow are created in educational licensed Ansys workbench 16.2 software as shown in Figure 3 and 4 respectively. As the geometries are symmetric about the axis, to take advantage of symmetry, the CFD analysis is done by considering the 2D axi-symmetric problem. Figure 3 shows the 2D axi-symmetric model of a missile in the air domain to study the pressure variations in the base of the missile at different Mach numbers. The radius of the base edge considered for the study is kept constant at 6 mm. The remaining dimensions of the domain in millimeters are shown in Figure 3.

The similar kind of pressure variations occurs at the blunt base of the duct when there is a sudden increase in the area of the duct. Figure 4 shows the 2D axi-symmetric model of pipe with a suddenly expanded duct to study the base pressure variations in the base corner of the duct at different Mach numbers. The length of the base edge is kept the same as the base radius of the missile shown in Figure 3, i.e., 6 mm to study and compare the pressure variations along the radial length.

The correctness of the results depends on the quality of the mesh. Mesh should be structured to get results in a reasonable time with accuracy. The model is divided into the number of parts, and each part has meshed separately with the structured grid. Figure 5 (a) and (b) shows the structured meshed models.

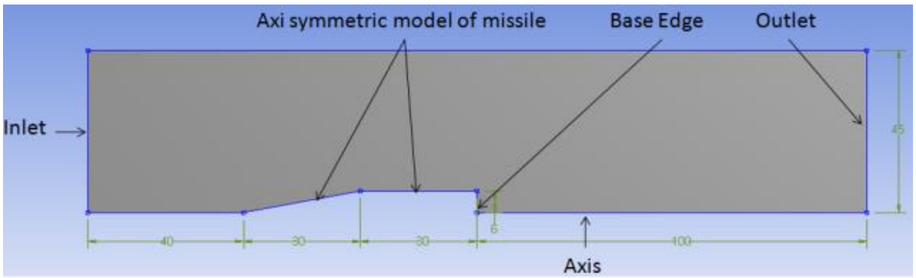


Fig. 3. The 2D axisymmetric geometry of a model in the flow domain to study external flow

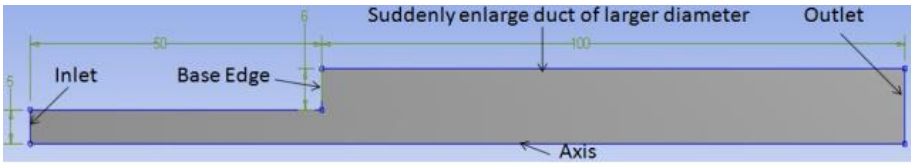
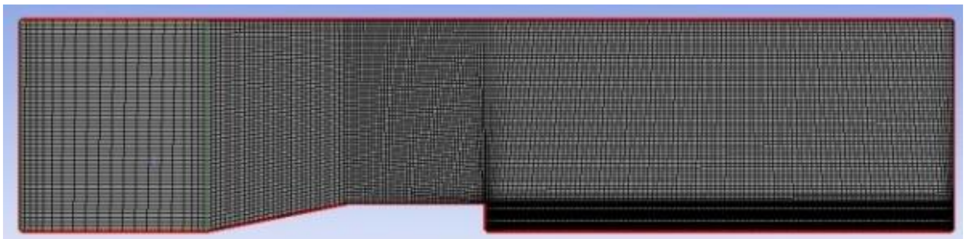


Fig. 4. The 2D axisymmetric geometry of pipe with an enlarged duct to study internal flow



(a) The 2D axisymmetric geometry of the model in the flow domain

(b) The 2D axisymmetric geometry of pipe with an enlarged duct

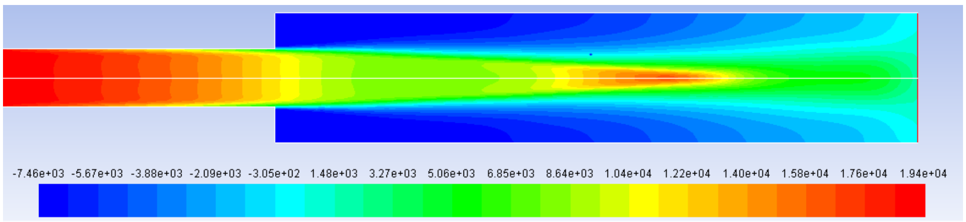
Fig. 5. Structured meshed models

CFD analysis has been carried out for both external flow and internal flow at Mach numbers 0.1 to 3.0. In boundary conditions, the inlet is considered as the velocity inlet and outlet as the pressure outlet. Inlet velocities are calculated according to different Mach numbers and assigned at the inlet boundary. The outlet pressure is set to be zero gauge pressure. The solver considered in the study was on density based and not on the pressure based. The reason to select the density base solution was to account for the compressibility effects and the effects of different inertia levels for the analysis [21]. The proper turbulence model selection is critical in CFD analysis. In the present study, the k-ε turbulence model is employed throughout the analysis. To achieve accuracy in the results the error in the range 10^{-6} is chosen and continued with the iterations until the solution convergence was achieved [10-13, 18-21]. The time taken by each case to converge was nearly 100 minutes, and approximately 4000 iterations.

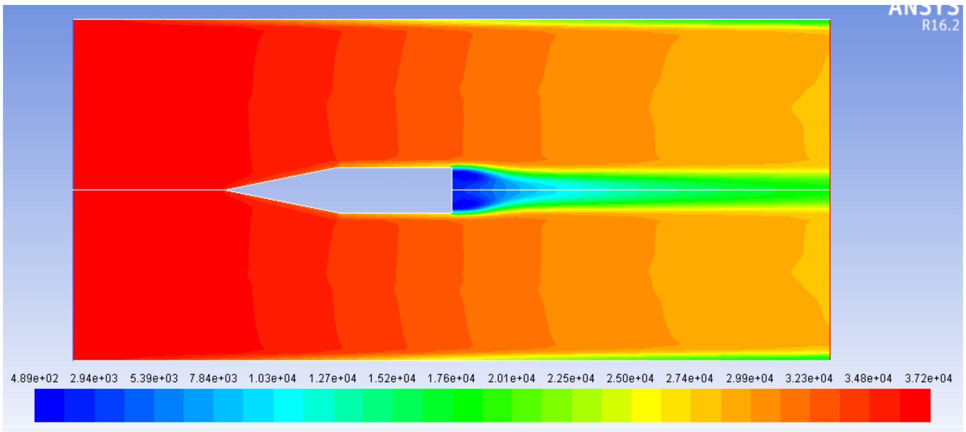
3. Results

Results are extracted in the form of pressure contours, and the average total pressures are calculated in the base region of internal and external flows with the help of ANSYS Fluent postprocessor. The contours of total pressure are shown in Figure 6 to 10 for both internal and external flows at different Mach numbers.

Figure 6 to 10 shows the pressure contours for different Mach numbers. From Figures 6 and 7 it can be seen that when Mach numbers are 0.5 and 1.0, the pressure distribution in the base region of internal and external flows are different. From Figures 8 to 10, it can be seen that when Mach numbers are from 2.0 to 3.0 the pressure distribution in the base region of internal and external flows are similar.

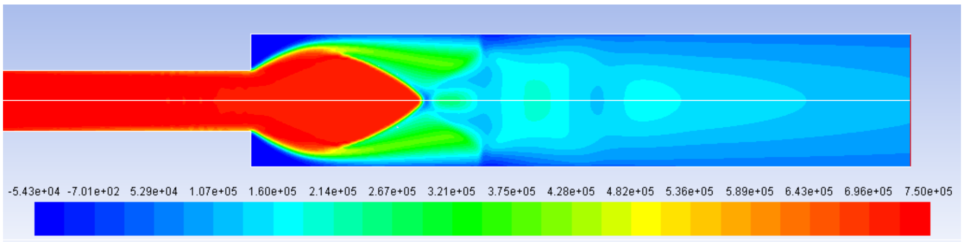


(a) Internal flow in a suddenly expanded duct

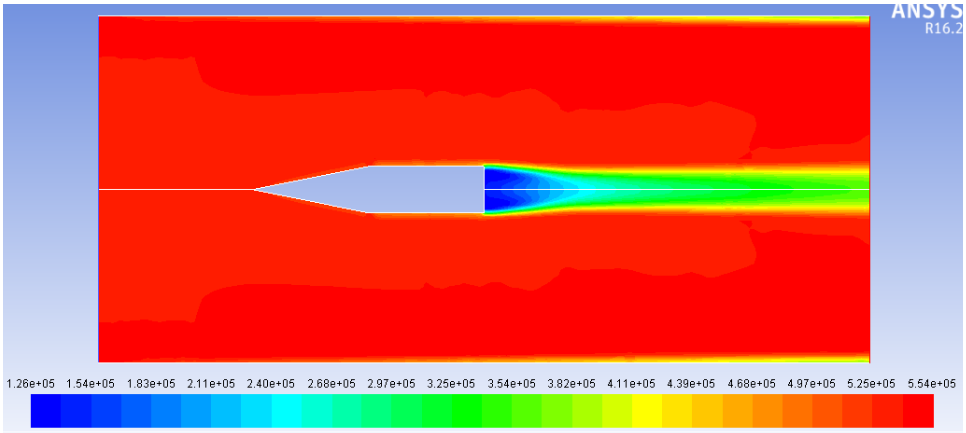


(b) External Flow over missile

Fig. 6. Pressure contour (in Pascal) at M = 0.5

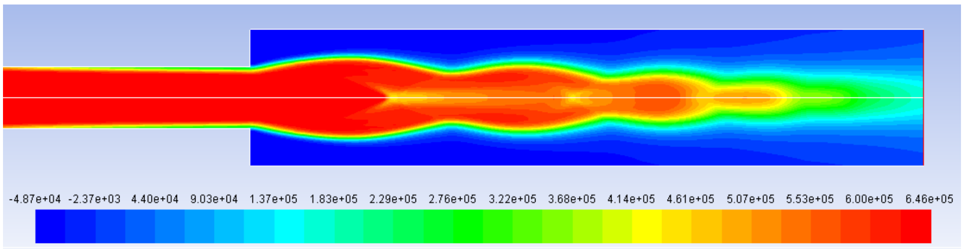


(a) Internal flow in a suddenly expanded duct

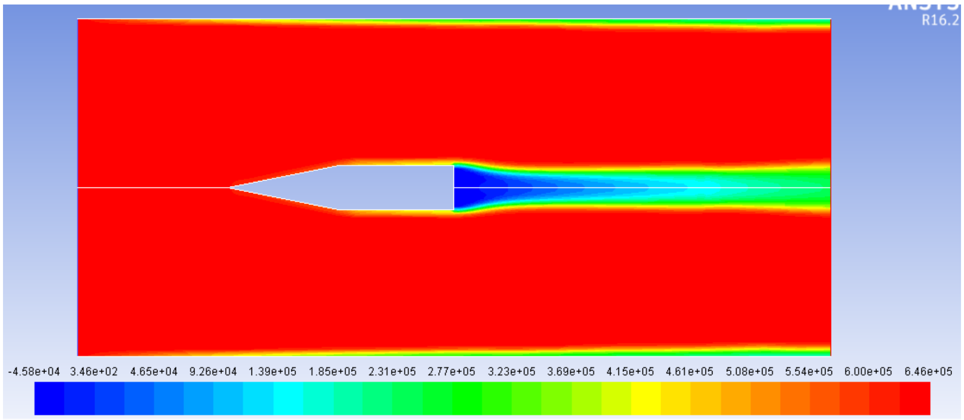


(b) External Flow over missile

Fig. 7. Pressure contour (in Pascal) at M = 1.0

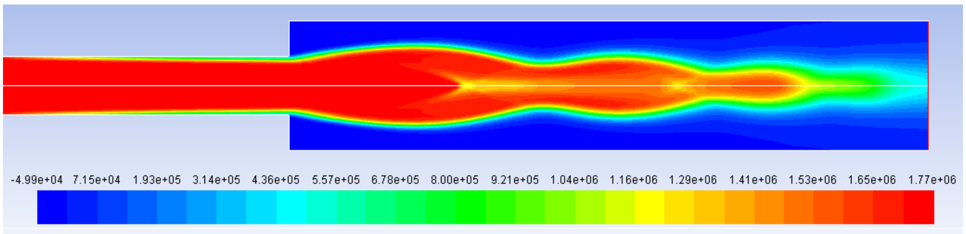


(a) Internal flow in a suddenly expanded duct

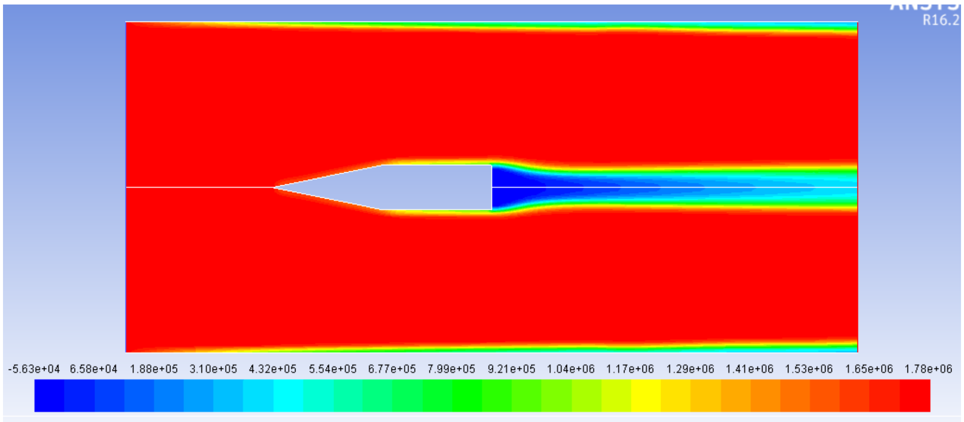


(b) External Flow over missile

Fig. 8. Pressure contour (in Pascal) at M = 2.0

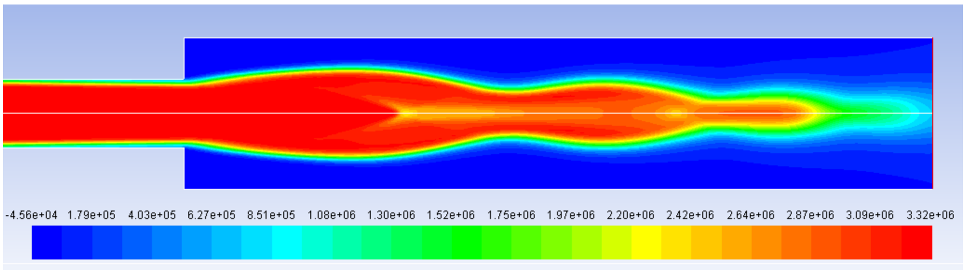


(a) Internal flow in a suddenly expanded duct

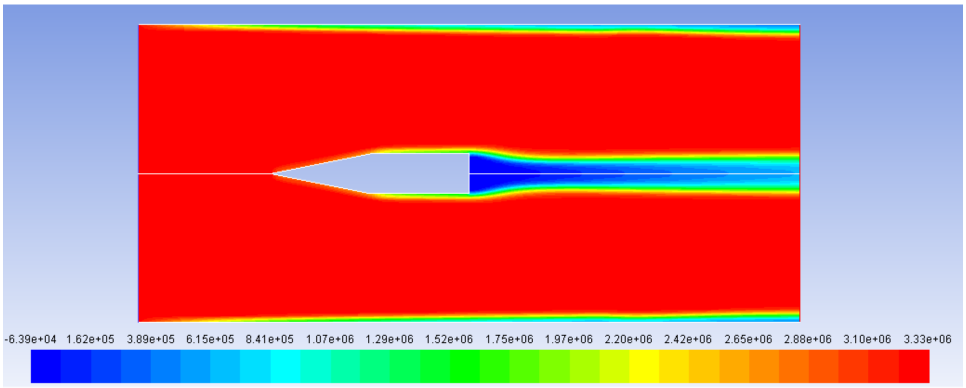


(b) External Flow over missile

Fig. 9. Pressure contour (in Pascal) at M = 2.6



(a) Internal flow in a suddenly expanded duct



(b) External Flow over missile

Fig. 10. Pressure contour (in Pascal) at M = 3.0

Further, the average base pressure is calculated in the base region of an enlarged duct, i.e., internal flow and in the base region of the missile, i.e., external flow for all the cases considered for the analysis and plotted in Figure 11. The pressure extracted from Ansys Fluent was gauge pressure which was converted into absolute pressure, and then the absolute pressure was divided by atmospheric pressure to convert it into non-dimensional base pressure.

Figure 11 shows the variations of non-dimensional base pressure for different Mach numbers. There is a peek at Mach 1 in external flow where the air is free to flow, and get separated, whereas, in the internal flow, the air is bounded by the wall of an enlarged duct hence it does not show the peak; instead it is showing a further depression in the base pressure value. This reduction in the base pressure value in the case of the internal flow is due to the separation of the shear layer. Due to the presence of the stable boundary, the shock gets hit the solid wall and then get reflected from the top and the bottom of the wall. Again there is the interaction of the waves, making the entire flow field very complicated. This peculiar behavior of the base pressure is expected as the flow field at Mach number unity is very complicated and very difficult to predict accurately.

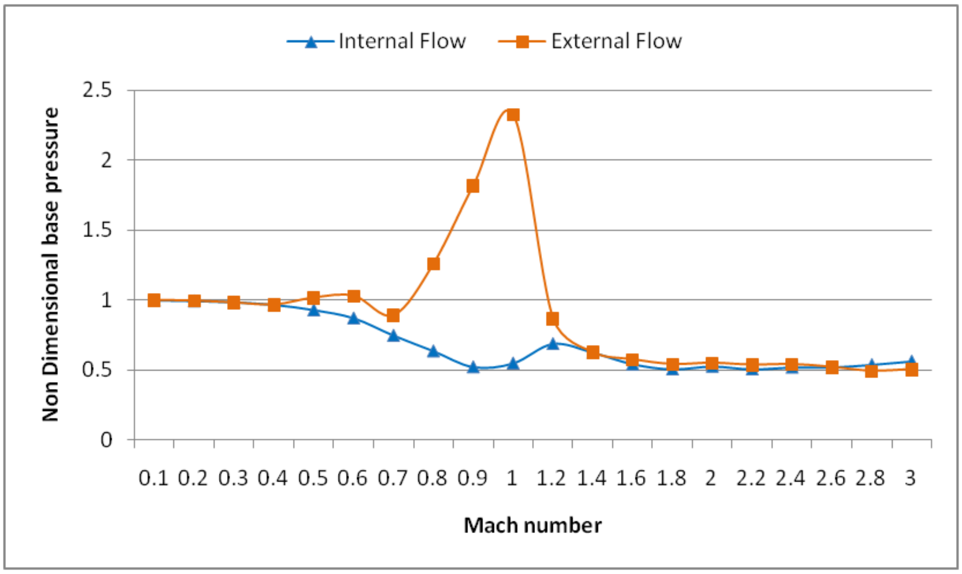


Fig. 11. Total base pressure Vs Mach number

4. Conclusions

The external flow and internal flow are principally the same. The experimental study of the base pressure with the internal flow is cost effective. In the case of internal flow, the measurement of the temperature and pressure along the axial and radial length can be done quickly, whereas, in the case of external flow these measurements are challenging experimentally.

Given the above discussions, the following conclusions may be drawn;

In internal flow, a considerable supply of air is reduced considerably and hence a reduction in cost for conducting the experimental investigations.

It is observed that the base pressure variations in case of external flow are nearly same as in case of internal flow for Mach numbers 0.1 to 0.4 and 1.4 to 3.0, except when the Mach number is very close to unity.

It can be concluded that the base pressure variations in the re-circulation region at the blunt base of the missile/projectile at the Mach numbers in the range of 0.1 to 0.4 and 1.4 to 3.0 can be analyzed very easily by investigating the problem as the internal flow problem with remarkable financial and computational ease.

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