Moderator Circulation Analysis for the Modified CANDU 6 Design using the CFD Code MODTURC_CLAS

by

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ABSTRACT

Steady-state moderator behaviour based on a full three-dimensional representation of the CANDU 6 calandria geometry is investigated using the CFD (Computational Fluid Dynamics) code MODTURC_CLAS for a proposed modified design. This modified CANDU 6 moderator design is geometrically identical to the standard CANDU 6 design, but with a different inlet nozzle/outlet port configuration. Infact, this modified design is similar to the CANDU 9 moderator design.

Under nominal operating conditions, analysis shows that the maximum temperature is reduced by 7°C compared to the maximum temperature observed for the standard CANDU 6 design. The effectiveness (stability) of this modified design is demonstrated by considering several case studies. It has been demonstrated that with an 18% reduction in the inlet mass flow rate and a mass flow imbalance into the two inlet headers (based on the nominal conditions), a minimum subcooling margin above 30 °C is maintained.

Solution dependence (in particular, the maximum temperature) on nodalization was investigated by performing a preliminary grid sensitivity study. It has been demonstrated that steady-state solutions for the modified design are relatively insensitive to grid refinement. Also, sensitivity to inlet mass flow rates for the modified design shows that the flow structure within the moderator is relatively insensitive to moderate design changes to input parameters.

1. INTRODUCTION

Computational Fluid Dynamics (CFD) has become an important tool for diagnosing problems, assessing safety, and improving designs to various heat transfer equipment. Within the Canadian nuclear industry, CFD has been used for reactor safety analysis. This paper presents steady-state moderator results based on a *full* three-dimensional representation of the CANDU 6 calandria geometry using the CFD code MODTURC_CLAS [1] for a proposed modified design.

Previous 2-D moderator design analyses have indicated that moderator circulation can be improved, and therefore, the maximum temperature within the existing CANDU 6 vessel can be significantly reduced by redirecting the inlet flow downwards and repositioning the outlet ports in the upper half of the calandria.

This modified design (known hereafter as the *modified* CANDU 6 moderator design) is geometrically identical to the standard CANDU 6 design, but with a different inlet nozzle/outlet port configuration. In this modified configuration, the inlet nozzles are located at the same positions as in standard design along the calandria length, with the nozzles pointing downwards, and the outlet ports located in the upper half of the calandria. This modified design has eight outlet ports (as opposed to two in the current CANDU 6 design), four on each side of the main shell, equally spaced axially 45° from the vertical. This modified design is similar to the CANDU 9 design, and can possibly enhance moderator safety and system performance.

2. DESCRIPTION OF THE CANDU 6 MODERATOR SYSTEM

The main features of the standard CANDU 6 moderator system are as follows. The calandria vessel is approximately 6 m long and 7.6 m in diameter at its widest point. There are 380 calandria tubes which displace about 12 percent of the calandria vessel volume. In addition, there are a number of horizontal and vertical reactivity mechanisms that run perpendicular to the calandria tubes.

The moderator fluid is heavy water. It is extracted from the vessel through two outlet ports located at the bottom of the vessel. The outlet ports are symmetrically located (axially) with respect to the mid–plane perpendicular to the x–axis but are asymmetrically located with respect to the z–axis in the y–z plane (see Figure 1). After discharging through the outlet ports, the moderator fluid mixes in a header and passes through one of two 100% pumps to be cooled via two 50% parallel heat exchangers, and is returned to the calandria through eight (8) inlet nozzles located on the circumference of the vessel in the reflector region (four nozzles on each side). The inlet nozzles are symmetrically placed (circumferentially) in the y–z plane with respect to the vertical centreline, but asymmetrically placed axially. The axial locations of the inlet nozzles and outlet ports are shown in Figure 2. A detailed illustration of a typical nozzle is shown in Figure 3.

Under nominal operating conditions, nuclear heat generation induces approximately 100 MW of power to the moderator fluid. The inlet coolant velocity is of the order of 2 m/s at the nozzle exits. Thus, the moderator fluid circulates within the calandria vessel due to the interaction of forced flow (caused by the inlet jets) and buoyancy flow (due to heat load), subject to the influence of a horizontal tube bank.

After leaving the calandria vessel, the heated fluid passes through two parallel heat exchangers (see Figure 4). Service water flow rate to the heat exchangers is controlled via the Moderator Temperature Control (MTC) program to maintain the moderator outlet temperature at 69°C. Under nominal full power conditions, the corresponding inlet temperature is approximately 46°C.

The total flow rate through the eight inlet nozzles is 940 *l*/s.

3. THE MODTURC_CLAS CFD CODE

General Description

MODTURC_CLAS (MODerator TURbulent Circulation using Co-Located Advanced Solution) is a computer code that has been developed jointly by Advanced Scientific Computing (ASC) Ltd., of Waterloo, Ontario and the Ontario Hydro Reactor Safety and Operational Analysis Department (RSOAD). It is a custom version of a more general code TASCFLOW [2] although the code has its own independent documentation [1]. The code was developed to predict temperature and hence subcooling distributions in the moderator of a CANDU reactor during large break loss–of–coolant accidents, in which the moderator is required to act as a heat sink. The problem requires advanced numerical techniques as moderator circulation combines the effects of forced convection due to inlet jets and natural convection due to internal heat generation in the fluid, in a complex geometry.

MODTURC_CLAS makes use of the most recent advances in computational methods to provide greater flexibility and economy in arriving at moderator temperature and flow predictions. It is a state-of-the art three–dimensional computational fluid dynamics computer code used to predict the flow and temperature fields of a single–phase turbulent incompressible fluid, subject to general boundary conditions in a prescribed geometry. The numerical method used in MODTURC_CLAS is a fully implicit, co-located, finite volume method with a flux element–based domain discretization. This combines the well known geometric flexibility of the finite-element method with the desirable conservation properties of the finite-volume method.

The governing partial differential equations for conservation of mass, Cartesian components of momentum, and energy form the basis of the governing equations in MODTURC_CLAS. The principal solution variables are the Cartesian components of velocity, pressure, temperature, and turbulent kinetic energy and dissipation, with all other variables being functions of these. The fully Cartesian co-ordinate system and co–located nodal arrangement for the solution variables utilised by MODTURC_CLAS avoids the complexity of a general tensor or non–orthogonal staggered grid formulation and, coupled with the numerically conservative finite volume approach, yields the desirable strong conservation properties.

Main Features of MODTURC_CLAS

Mathematical models have been incorporated into MODTURC_CLAS describing various physical phenomena that develop/occur within the moderator:

- The effect of the calandria tube matrix (also known as the core) on the flow distribution is approximated using the porous media concept in which the reduction in flow volume is accounted for by defining an isotropic volume–based porosity (defined as the fluid–filled volume, divided by the total fluid and solid volume). The flow around individual calandria tubes is not modelled in the analysis (due to computer time and memory constraints). The porosity model is a user option in MODTURC_CLAS;
- The anisotropic hydraulic impedance of the tubes is modelled using empirical friction factor correlations based on tests performed at STERN Labs in Hamilton, Ontario [3];
- Buoyancy forces are modelled using the Boussines'q approximation in which density is assumed to be a linear function of temperature; and
- The two equation standard k–ε model is employed to model turbulence generation and dissipation within the vessel. Since the flow is in the high Reynolds number regime (in the order of 10^6 to 10^7), use of this model also requires the use of wall functions to account for near wall viscous effects. The k-ε turbulence model and corresponding wall functions are standard user options in MODTURC_CLAS.

4. MODTURC_CLAS VALIDATION and APPLICATION

MODTURC_CLAS has undergone extensive validation against small scale tests performed at STERN Labs in Hamilton, Ontario. The small scale test facility embodied all of the salient features of a typical CANDU 6 calandria, i.e., inlet jets, a tube–matrix (representative of the CANDU core), and internal heat generation. Several experimental tests were performed at STERN Labs including both isothermal and heat addition cases. A description of the test facility and comparisons between MODTURC_CLAS and experimental measurements can be found in [4 and 5]. For this reason, it is deemed appropriate to use MODTURC_CLAS for CANDU 6 moderator circulation analyses. MODTURC_CLAS has also been validated against in-core measurements taken in the Bruce A and Pickering B calandrias.

In addition to the current work, steady-state and LOCA/Loss of Class IV Power transient analyses have been performed using MODTURC_CLAS for the CANDU 9 moderator system. Other accident scenario results for the CANDU 9 moderator system (e.g., LOCA/LOECC) using MODTURC_CLAS has recently been analysed. Modelling of coolant/poison mixing in the calandria during a postulated fuel channel rupture for the Bruce Nuclear Generating Station B has also been analysed [6].

5. MODELLING DETAILS AND ASSUMPTIONS

The MODTURC_CLAS Full Calandria Model

The calandria vessel is an indented cylinder 5.944 m long with a main shell diameter of 7.6 m and a subshell diameter of 6.76 m. Each of the subshells has a length of 0.97 m (see Figure 1). MODTURC_CLAS has an option to "block-off" control volumes in the solution domain. This implies no flow in such a region. Since the subshell has a smaller diameter than the main shell it is necessary to implement this feature of the code by blocking out off the relevant cells in the subshell region. The volume occupied by in–core devices is not accounted for in the present analysis, as it is small compared to the total volume of the calandria tubes. It is assumed that these devices do not affect the local flow appreciably. The volume occupied by the nozzle housings is also blocked-off.

Proposed Modified Full 3-D Calandria Model

The modified calandria design is geometrically identical to the standard CANDU 6 design, but with a different inlet nozzle/outlet port configuration, that is,

1) The inlet nozzles are placed in the same locations, pointing downwards; and
2) The outlet ports are relocated in the upper half of the calandria, there being eight outlet ports (as opposed to two) in the modified design (four on each side of the main shell, equally spaced axially 45° from the vertical). Each of the outlet ports is 6" in diameter. (This calculation is based on equating the total cross-sectional area (72π in^2) of the two outlet ports of the standard CANDU 6 design with the total cross-sectional area of eight (8) outlet ports in the modified CANDU 6 design).

The inlet nozzles are located below the horizontal centreline (~ 10°) at the same circumferential position as the current standard CANDU 6. T_{max} within the vessel will be the primary comparison output. This will give us the best available estimate in the improvement in T_{max} over the current CANDU 6 design.

Grid Selection

The finite-element grid generation capabilities of MODTURC_CLAS were used to advantage in generating the grid to be used in the analysis. A butterfly grid was chosen to represent the cross-section of the calandria. That is, in the core region, a coarse mesh is employed since we are using the porous media approach for flow in that region (and there is no justification in prescribing grid elements smaller than the calandria tube cross–section since we are not modelling flow around the individual calandria tubes). In the reflector region a polar grid using a fine radial grid (throughout the entire angular domain $0–2\pi$) and a fine angular grid in the vicinity of the jets is employed in order to capture the realistic behaviour of the inlet jets (e.g., attachment to the vessel wall).

Figure 5 shows a schematic of the standard CANDU 6 grid in the Y–Z plane perpendicular to the cylindrical axis of the calandria with the nozzles blocked-off. Figure 6 shows the standard 3-D full wireframe grid.

Figure 7 illustrates the MODTURC_CLAS representation of a typical inlet nozzle. These cells are blocked-off in the simulations (as shown in Figure 5). For the standard CANDU 6 design, the number of cells in the full grid is approximately 51,000 cells, with 22,000 cells (finer grid) immediately downstream of the inlet nozzles, and 29,000 cells in the remainder of the domain. In the modified design, a total of 63,000 cells (including 28,000 cells downstream from the inlet nozzles) were used. The modified CANDU 6 grid with the inlet nozzles blocked-off is shown in Figures 8 and 9.

6. STEADY-STATE SOLUTION

Heat Load and Inlet Flow Rate for Steady-State Analysis

At nominal power, the total heat load, Q_{tot}, is taken to be 100 MW, 6 MW to the reflector region and 94 MW to the core. The local heat load to the moderator is assumed to be proportional to the local bundle power. Time averaged bundle power maps were used.

The total inlet flow rate, m_{tot}, is 940 *l*/s (or 1024 kg/s). This flow rate is assumed to be equally distributed to each of the eight inlet nozzles. Each nozzle is fanned-shaped with the flow emanating from the four (flux) compartments (as shown in Figure 8). It was assumed that for each nozzle, the inner two compartments accommodate 62.5% of the flow, and the outer two compartments accommodate 37.5% of the flow. Also, across each face of the exit compartment, a uniform velocity was assumed, although non-uniform velocities across each compartment face were observed in the Stern Laboratory tests.

Results and Discussions

MODTURC_CLAS models (employing discretization of the entire calandria) for both the modified CANDU 6 design and the standard CANDU 6 design were generated. T_{max} within the vessel is the primary comparison output. The steady-state solution was deemed converged when the maximum residuals reached a value less then $5x10^{-5}$. It was found that a converged solution takes approximately two to three CPU days on a HP 9000 K200 machine (with 4 PA-RISC 7200 CPUs [32-bit] and 768 MB RAM running HP-UX 10.01).

<u>Reference Case: Nominal Operating Conditions</u>

A comparison of the MODTURC_CLAS solutions based on the modified CANDU 6 design with the standard CANDU 6 design is made using the operating conditions mentioned previously. This comparison shows that by redirecting the inlet nozzles downward, and by relocating the outlet ports to the upper half of the calandria, T_{max} is reduced and, in addition (due to the location of T_{max}) subcooling margins are increased.

Shown in Figures 10a and 11a, respectively, are the velocity plots for the standard CANDU 6 and the modified model design at x=3.0 m (mid-length of the calandria). Also shown in Figures 10b and 11b, respectively, are the corresponding temperature contours for the the standard CANDU 6 and the modified designs at x=3.0m. In these plots, the flow structure and the temperature fields are distinctly different for the two configurations. The flow structure is different because, for the standard CANDU 6 geometry, the relatively "cool" moderator fluid is injected upwards. As this cool fluid is directed to the top, heat transfer occurs from the hot surrounding fluid below. Also, because this fluid is relatively cooler than the surrounding fluid, it will have the tendency to "sink". There is also the rising hot fluid (due to buoyancy) which displaces the cool fluid. The balance of these effects (both inertial and buoyancy driven) determines where the jets collide. In the present case, the jets collide near the top (at the one o'clock position), and are redirected into the core.

As it penetrates the core, this relatively cool fluid advects heat away from the core. At the upper left portion of the core, a pocket of hot fluid is created due to the rising fluid from below. As a result, a recirculating zone of hot fluid is created. Figure 11a shows that the maximum temperature occurs in this region.

For the modified CANDU 6 design, the velocity and temperature contour plots resemble those of the CANDU 9 velocity and temperature contour plots reported in Reference 8. The cool fluid is directed downwards and collides at the bottom, and is redirected up into the core. This fluid then heats up and rises. As it rises, it is removed via the eight outlets located near the top. The complementing nature of this (stable) flow (cool fluid directed to the bottom and hot fluid displaced to the top, as opposed to the counter-acting (unstable) flow seen in the standard CANDU 6 geometry) gives rise to the stratified temperature field as shown in Figure 11b. As expected, the maximum temperature is at the top of the calandria.

Grid Refinement Downstream from the Inlet Nozzles

A finer grid downstream from the nozzles was generated, and MODTURC_CLAS steady-state solutions based on the nominal operating conditions were obtained. This subcase has been denoted by "Reference A" in Table 1. This refinement study is required to determine whether the chosen grid is adequate to describe the momentum distribution across the nozzle exit and subsequent jet development, and most importantly, how it affects T_{max}. This is important for both standard and modified CANDU 6 designs.

Table 1 shows that with this refined grid, there is a more significant difference in the converged solution for the standard CANDU 6 geometry than the modified CANDU 6 geometry. Without grid refinement, a higher local momentum flux emanates[1] from the nozzle inlets, although global momentum transfer is strictly adhered to. As a result, higher velocities are noticed at the symmetry plane of each nozzle (and consequently lower at the outer edge of the nozzle), resulting in greater penetration of the jet into the core. The

[1] A direct consequence of the treatment of boundary condition information in MODTURC_CLAS's discretization scheme.

effect of this locally higher flow influences the local flow distribution, and hence decreases T_{max} from 80.9 °C to 76.7 °C.

For the modified CANDU 6 geometry, the effect of grid refinement at the nozzle exit is rather small. This is attributed to the stable nature of the flow, as indicated above.

Based on the analyses performed for this reference case (with grid refinement), the reduction in T_{max} (in the modified design compared to the standard design) is approximately 7°C, and there is an increase in the subcooling margin to 35 °C.

The following section investigates the effect of T_{max} to reduced inlet mass flow rates and "side-to-side" flow imbalance into the inlet nozzles for the modified design. These cases incorporate the grid refined model.

Case 1: Reduced Inlet Mass Flow Rate

The sensitivity of the total mass flow rate on T_{max} and therefore, $\Delta T_{min, subcool}$ was investigated for the modified CANDU 6 design. In the first case, denoted by Case 1a, a reduction of the inlet mass flow rate from 1024 kg/s to 940 kg/s (keeping other inlet parameters unchanged) was considered. Due to the reduced flow, as expected, there is an increase in the outlet temperature and in the bulk temperature. The velocity and temperature contour plots (not shown here) are similar to the nominal case shown in Figures 11a and 11b. This case indicates that a stratified temperature field still exists, and (as expected) the flow structure remains unaffected by the reduced inlet flow rate.

In the second case (Case 1b), the inlet flow rate was further reduced to 840 kg/s. (In fact, this value was selected so that, based on the total heat load of 100 MW, the outlet temperature was maintained at 74 °C). Similar to Case 1a and the reference case, the temperature field remains stratified (also not shown). A summary of output variables obtained from MODTURC_CLAS for these two subcases is listed in Table 1.

With reduced inlet flow rates (down to 840 kg/s), T_{max} increases, yet the subcooling margin remains above 30 °C.

Case 2: Side-to-Side Mass Flow Imbalance

To represent a physically realistic mass flow distribution to the two inlet headers (due to piping losses), a "side-to-side" mass imbalance flow case was considered. It was assumed that 45% of the total mass flow is distributed to one header, and 55% to the other header, with the same total mass flow rate (1024 kg/s) emanating from the eight inlet nozzles. Within each header, the flow rate was equally distributed to each of the four nozzles.

Figure 12a shows the flow field, and as expected, the jets collide away from the six o'clock position. The location is primarily based on the balance of inertial forces, and in this case, it is located around the eight o'clock position. As seen in Figure 12b, a stratified temperature field is still maintained, the only difference being the location of the minimum temperature.

7. CONCLUDING REMARKS

The MODTURC_CLAS results for the modified design indicate that:

- both the flow and temperature fields are insensitive to grid refinement in the vicinity of the nozzles and to the more realistic unequal inlet mass flow rates to the inlet headers. These case studies demonstrate the stability of the modified design; and
- under nominal operating conditions, the modified CANDU 6 design reduces T_{max} by 7°C and the minimum subcooling margin is kept above 30°C.

8. ACKNOWLEDGEMENTS

The authors would like to thank Hydro-Quebec and Ontario Hydro for permission to use their MODTURC_CLAS half calandria model as a starting point for this analysis.

9. REFERENCES

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2. TASCFLOW, "Theory Documentation", Version 2.2, April 1993, Advanced Scientific Computing Ltd., Waterloo, Ontario, Canada.
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4. Huget, R.G., Szymanski, J.K., Midvidy, W.I., "Status of Physical and Numerical Modelling of CANDU Moderator Circulation", CNS Annual Conference, Ottawa, 1989 June 4–7.
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6. Mackinnon, J., and Szymanski, J., "Modelling of Coolant/Poison Mixing in the Calandria of a CANDU Nuclear Reactor using MODTURC_CLAS", CFD 95, Banff Alberta, June 26-27, 1995.

Case	Total Inlet mass flow (kg/s)	Grid Refinement ?	T_{max} (°C)	$\Delta T_{min, subcool}$ (°C)	Location of T_{max} (m)
Reference (Standard CANDU 6)	1024	No	76.7	32.7	(3.4, 1.5, 2.4)
Reference A (Standard CANDU 6)	1024	Yes	80.9	28.9	(1.8, -2.5, 1.3)
Reference (Modified CANDU 6)	1024	No	74.5	34.9	(5.0, 2.2, 3.1)
Reference A (Modified CANDU 6)	1024	Yes	74.3	35.0	(1.0, 2.9, 2.4)
1a	940	Yes	76.2	32.7	(1.0, 2.6, 2.8)
1b	840	Yes	78.4	30.2	(1.0, 2.6, 2.8)
2	1024	Yes	74.2	34.7	(1.0, 2.2, 3.1)

Table 1: Summary of 3-D Full Calandria MODTURC_CLAS Steady-State Results.

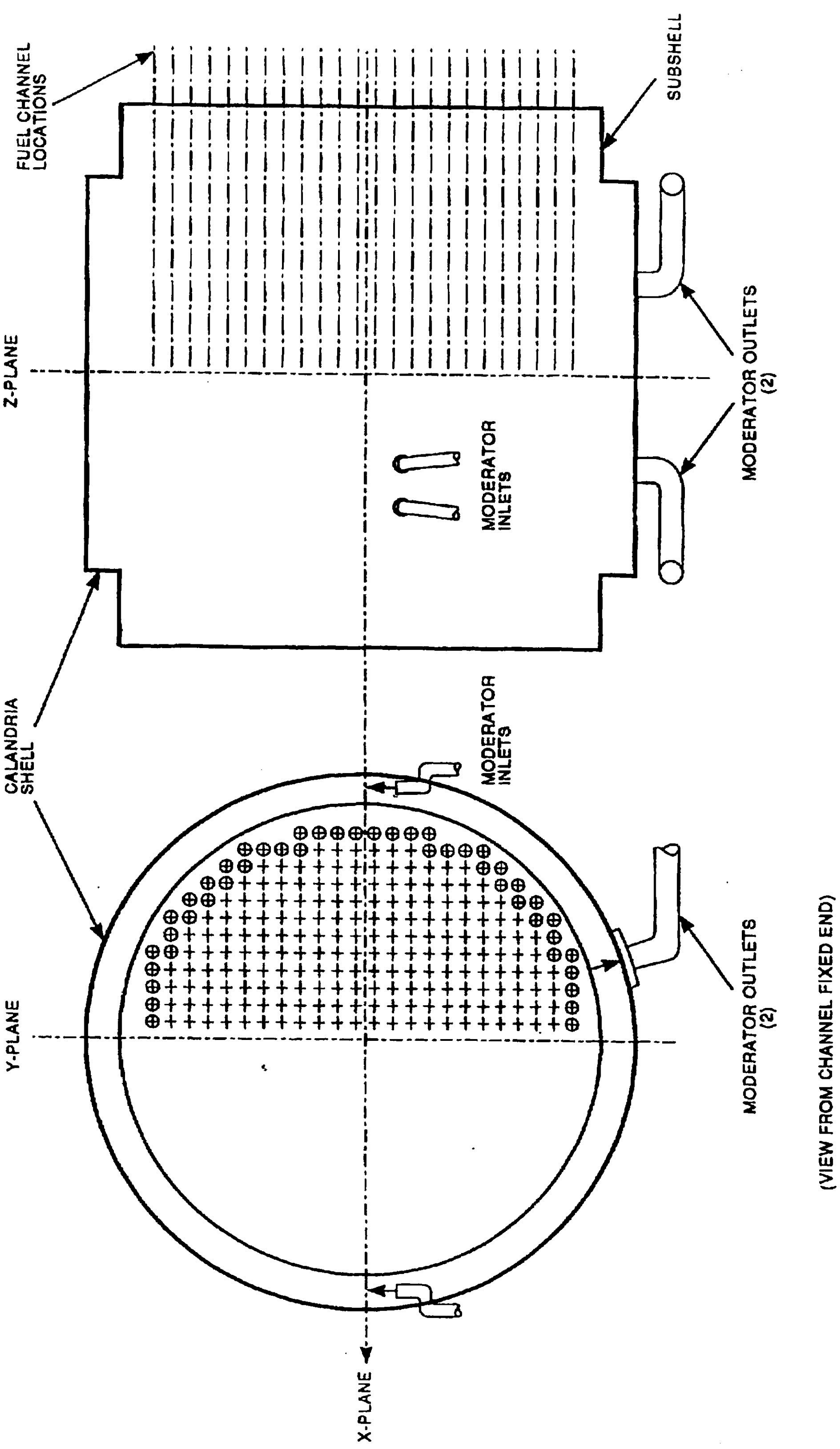

Figure 1: Standard CANDU 6 Moderator System.

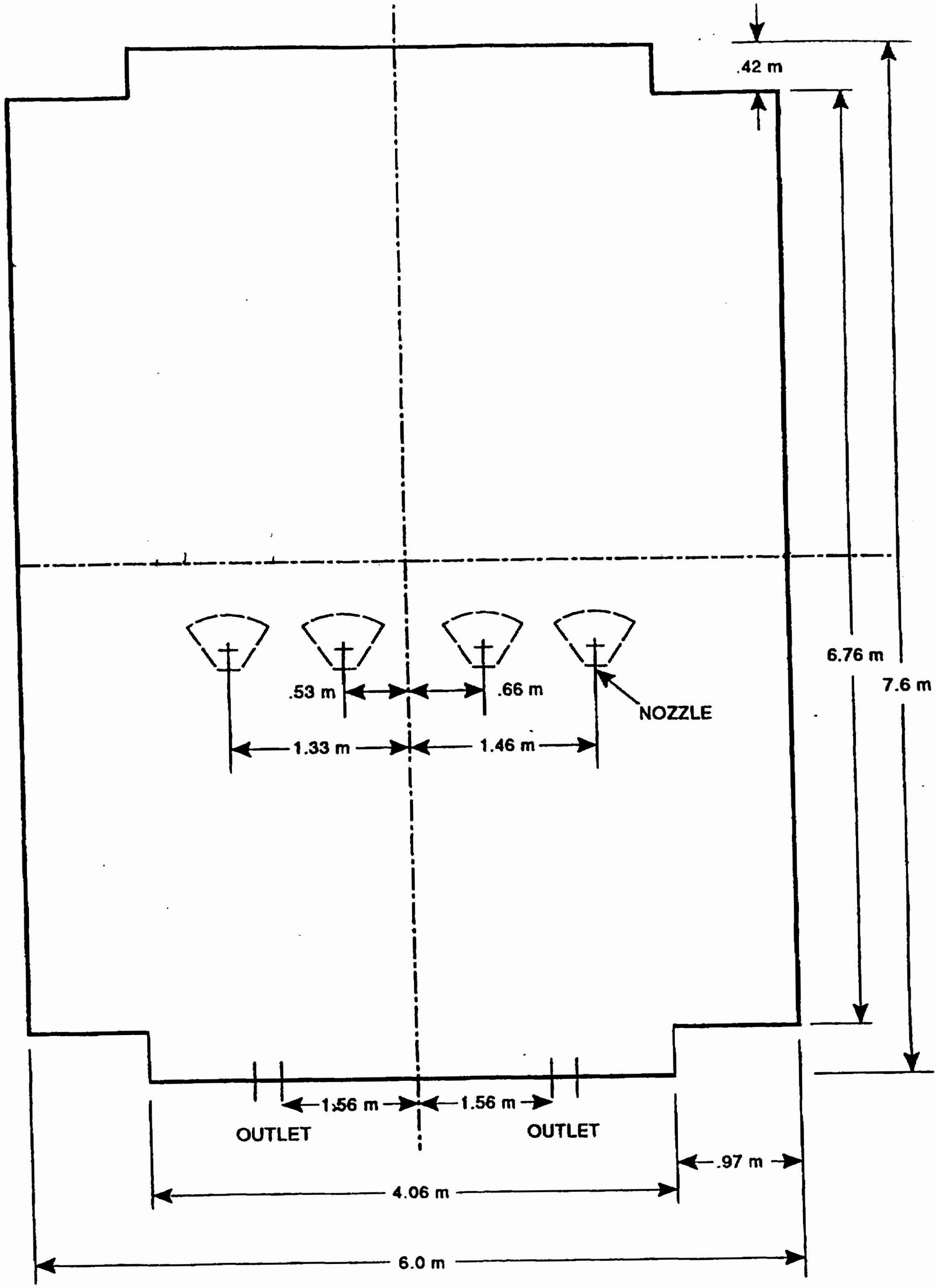

Figure 2: CANDU 6 Calandria Vessel Side View.

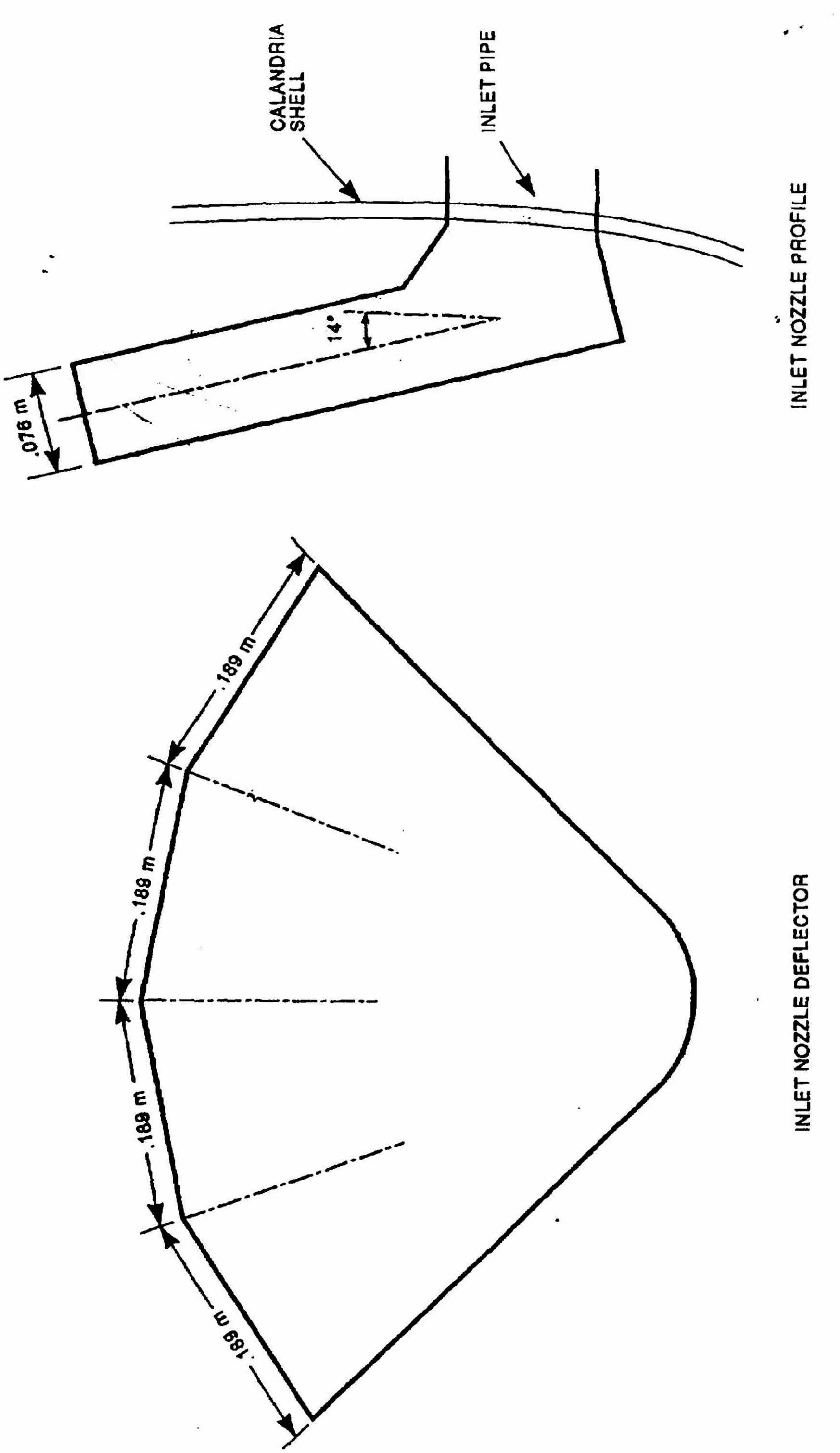

Figure 3: Inlet Nozzle Geometry.

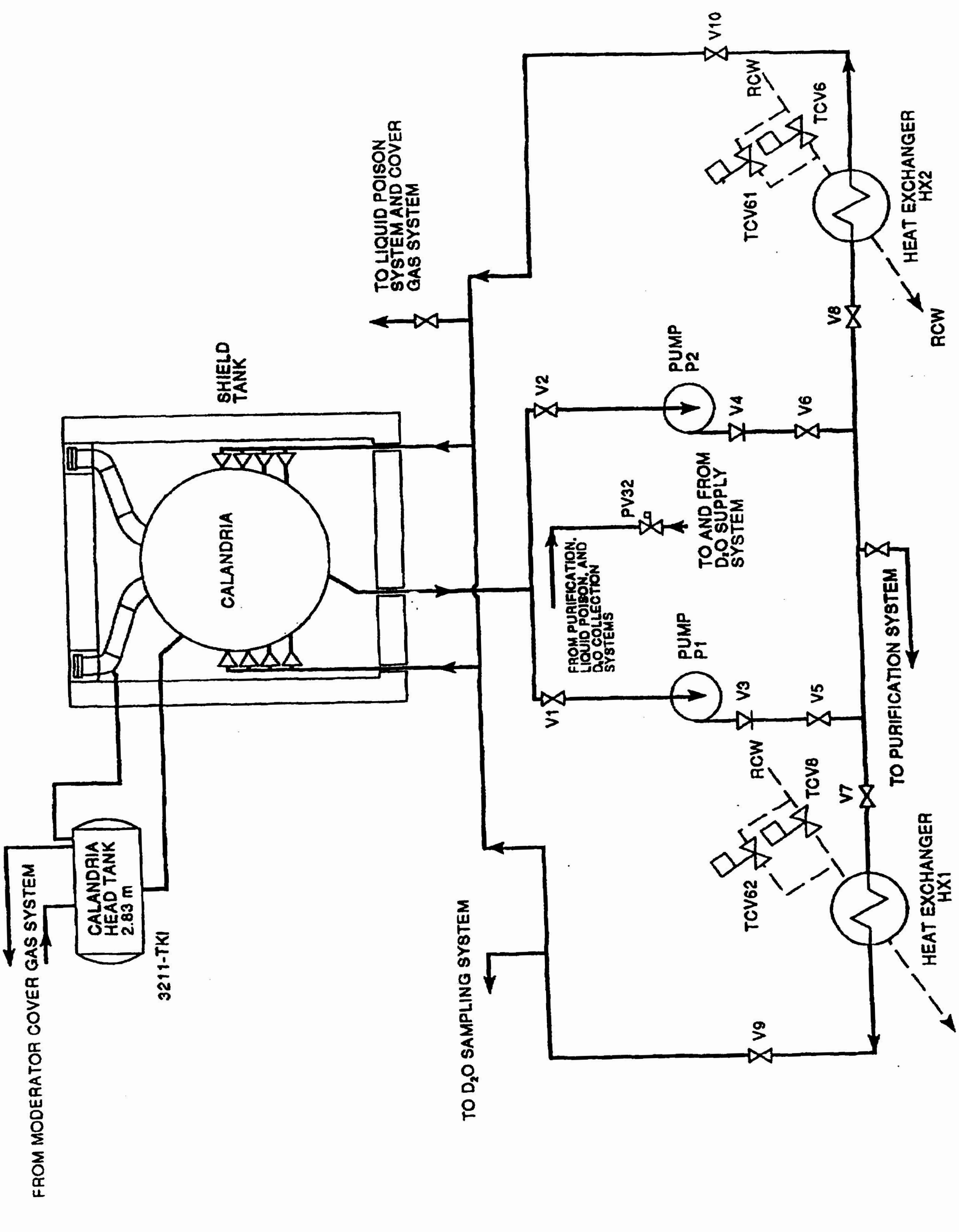

Figure 4: Schematic of CANDU 6 Main Moderator System.

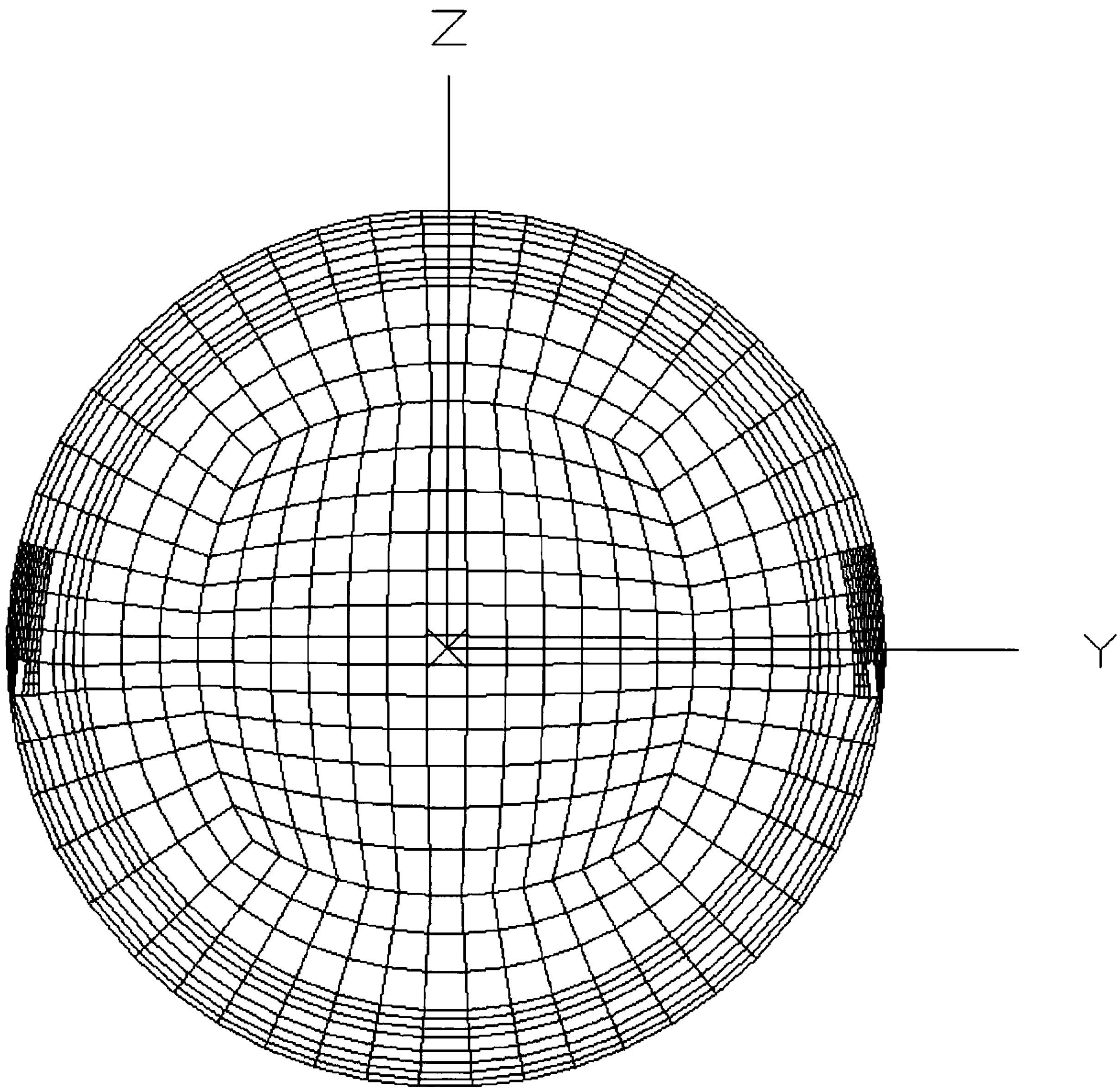

Figure 5: Standard CANDU 6 MODTURC_CLAS Representation of the Moderator Cross Section (in the Y-Z Plane).

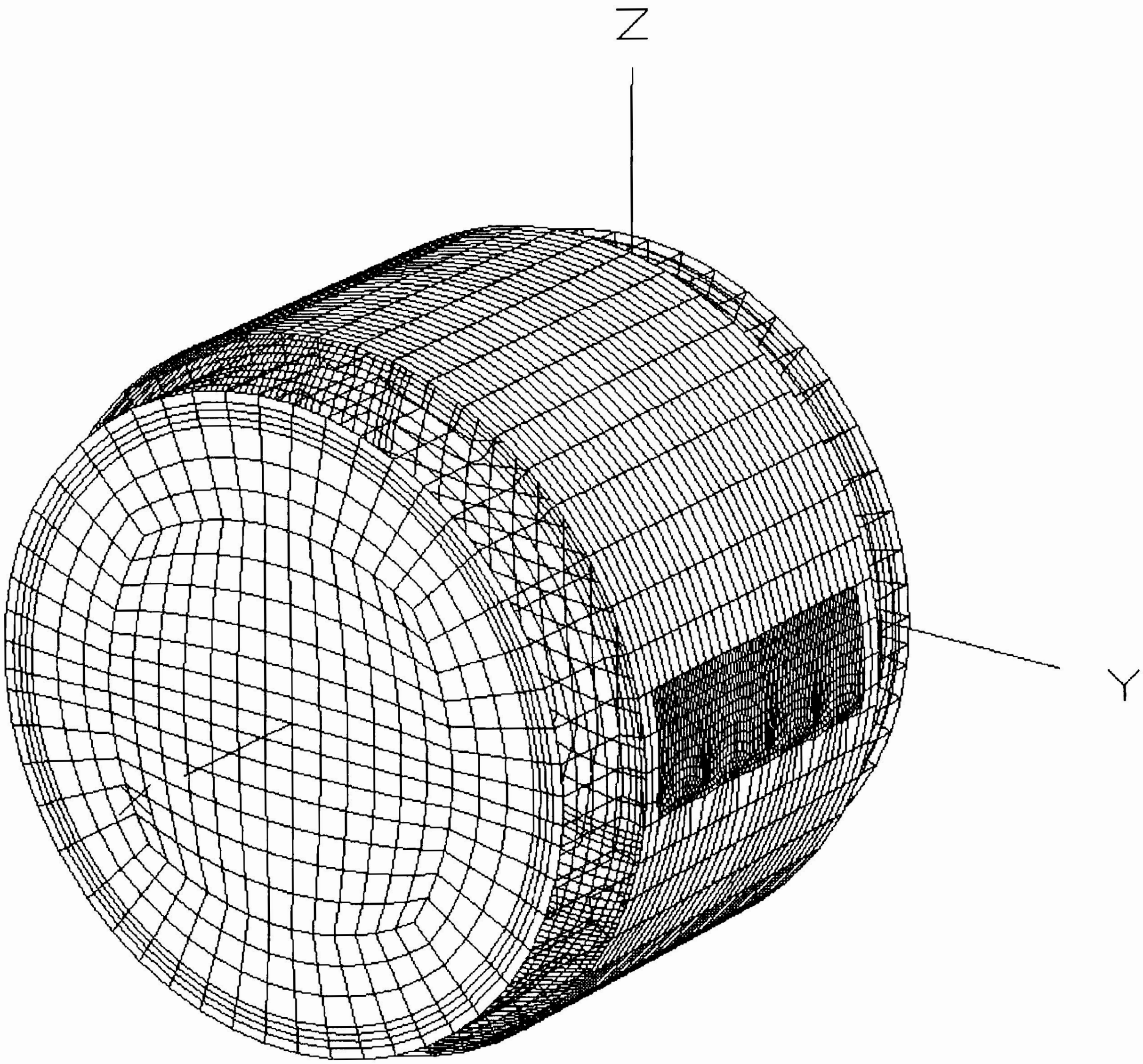

Figure 6: Three-Dimensional Wireframe Grid of the Standard CANDU 6 Geometry.

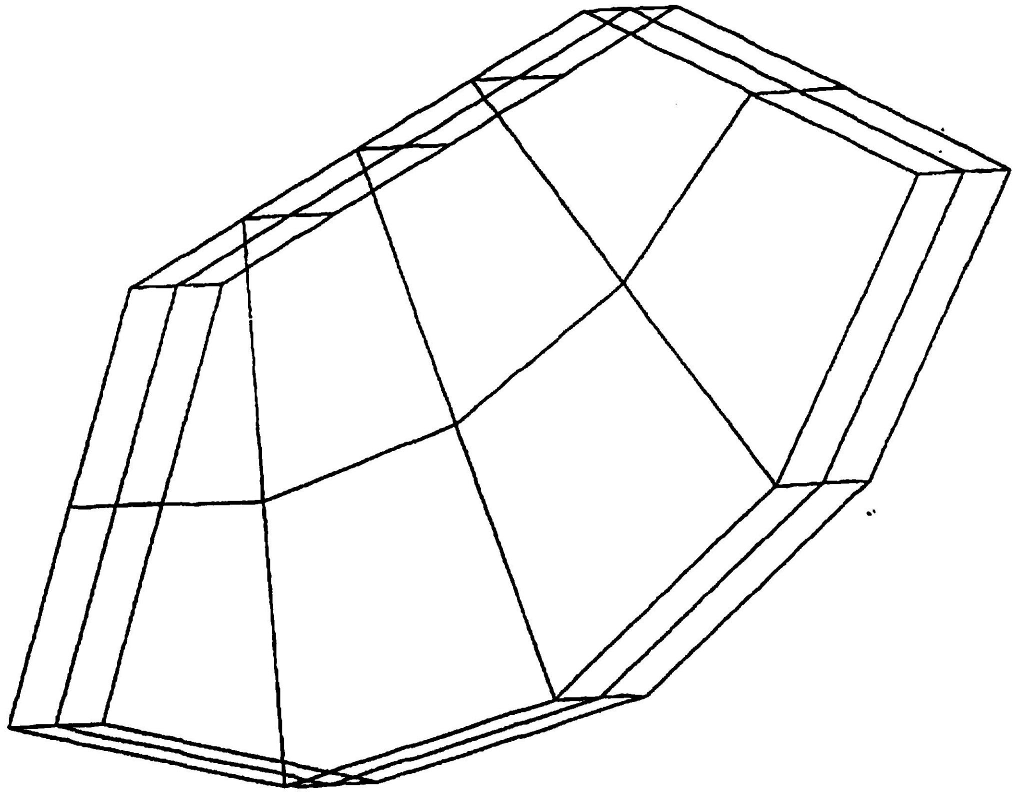

Figure 7: MODTURC_CLAS Representation of a Typical Inlet Nozzle.

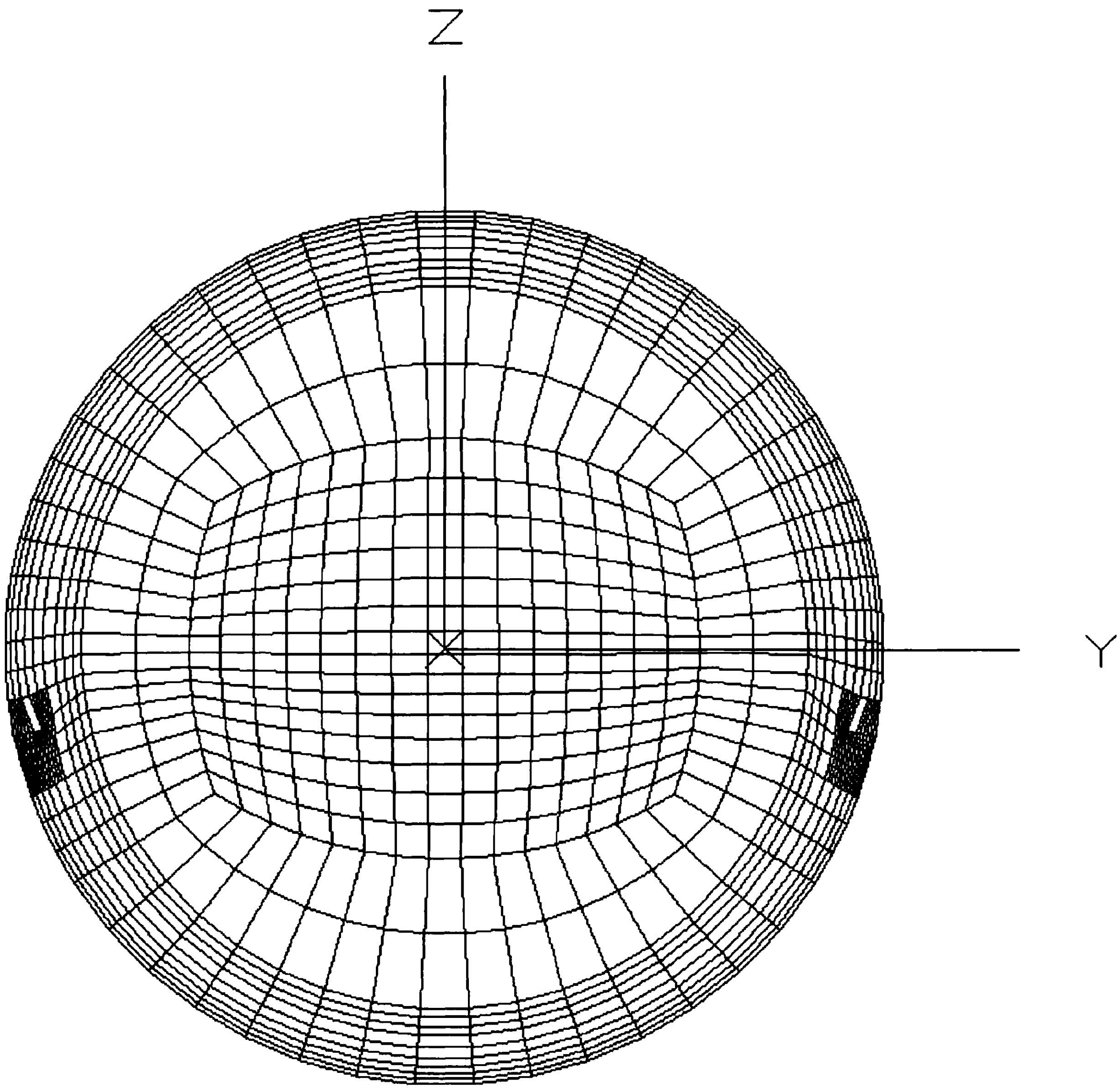

Figure 8: Modified CANDU 6 MODTURC_CLAS Representation of the Moderator Cross Section (in the Y-Z Plane).

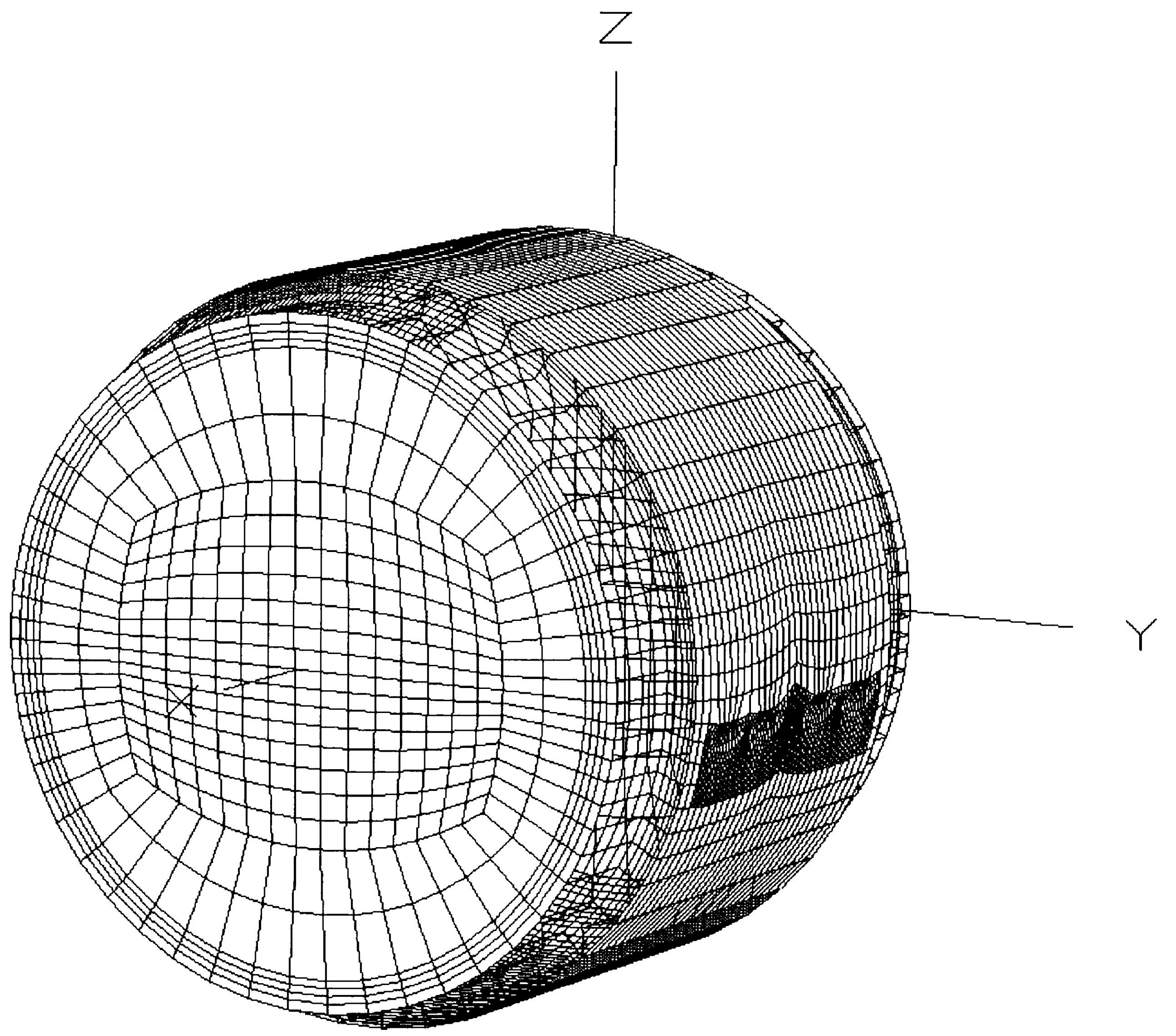

Figure 9: Three-Dimensional Wireframe Grid of the Modified CANDU 6 Geometry.

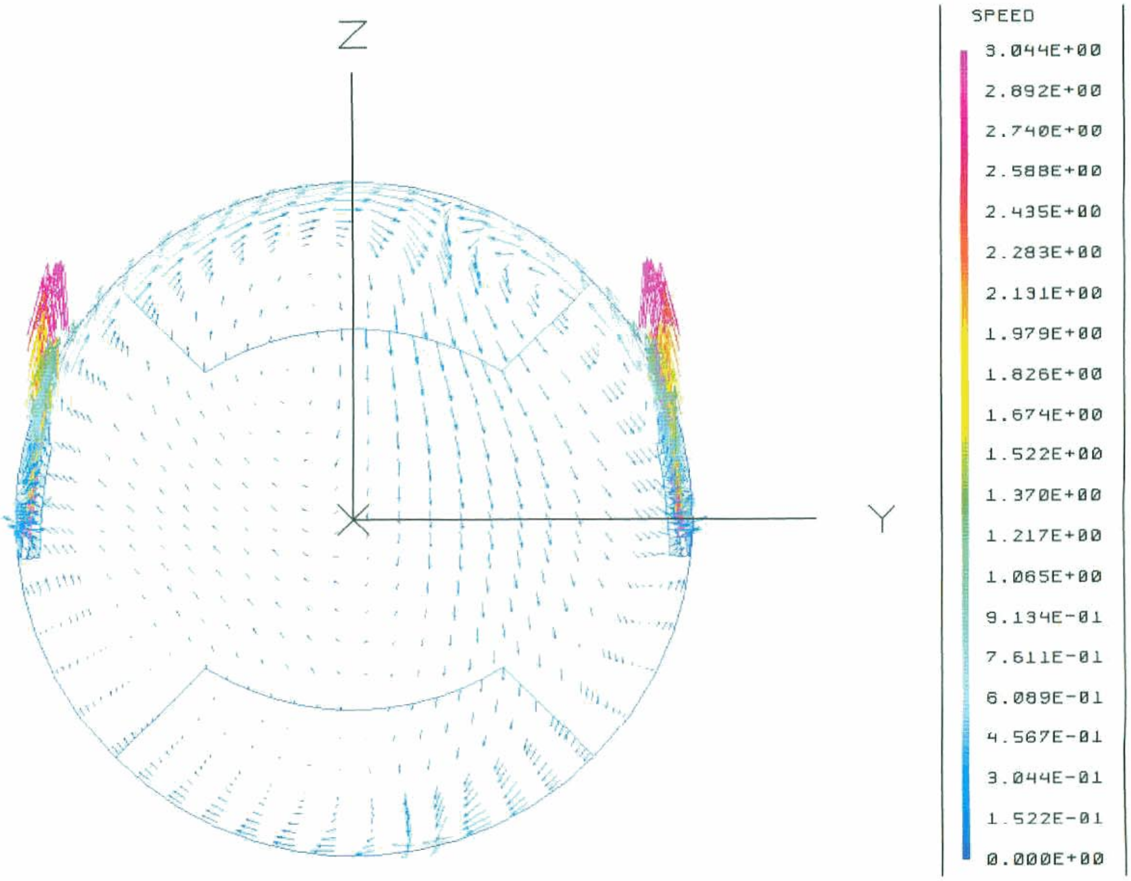

Figure 10a: Steady-State Velocity Vector Plot for the Standard C6 Geometry in a Nozzle Plane (Reference Case).

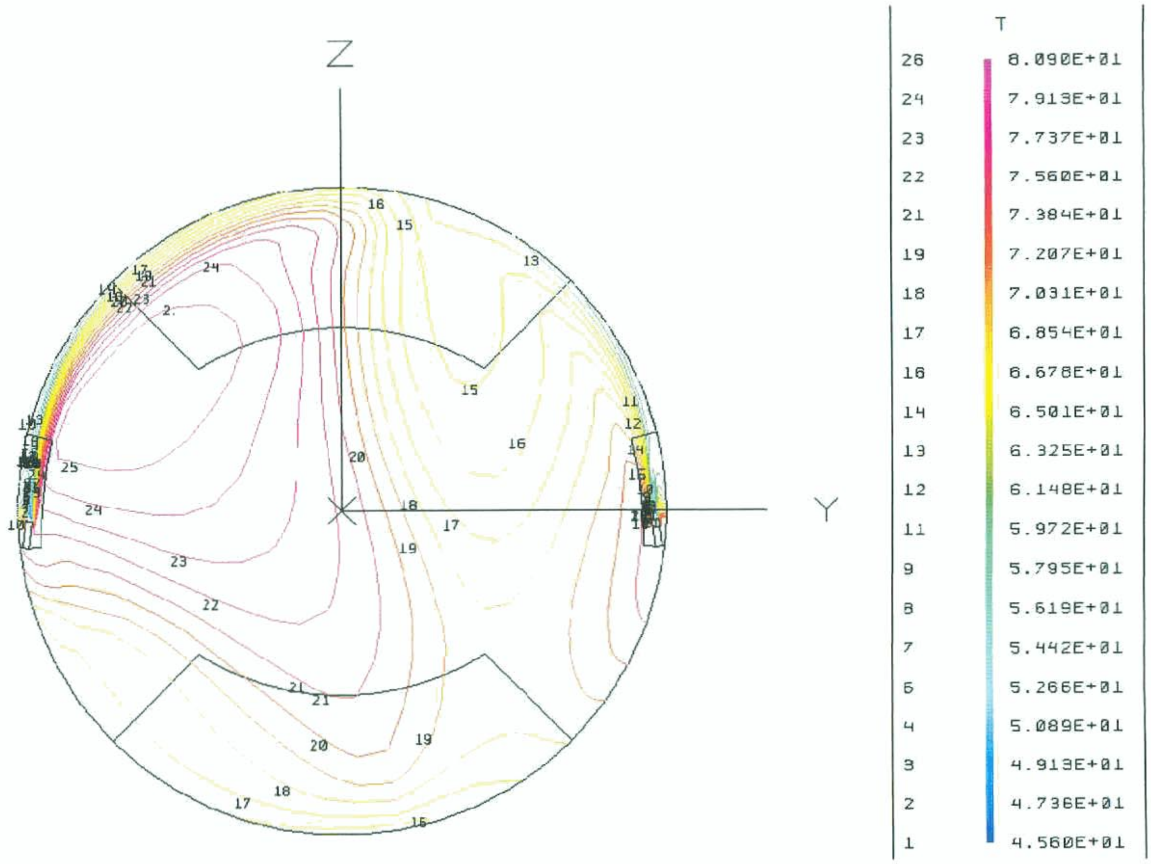

Figure 10b: Steady-State Temperature Contour for the Standard C6 Geometry in a Nozzle Plane (Reference Case).

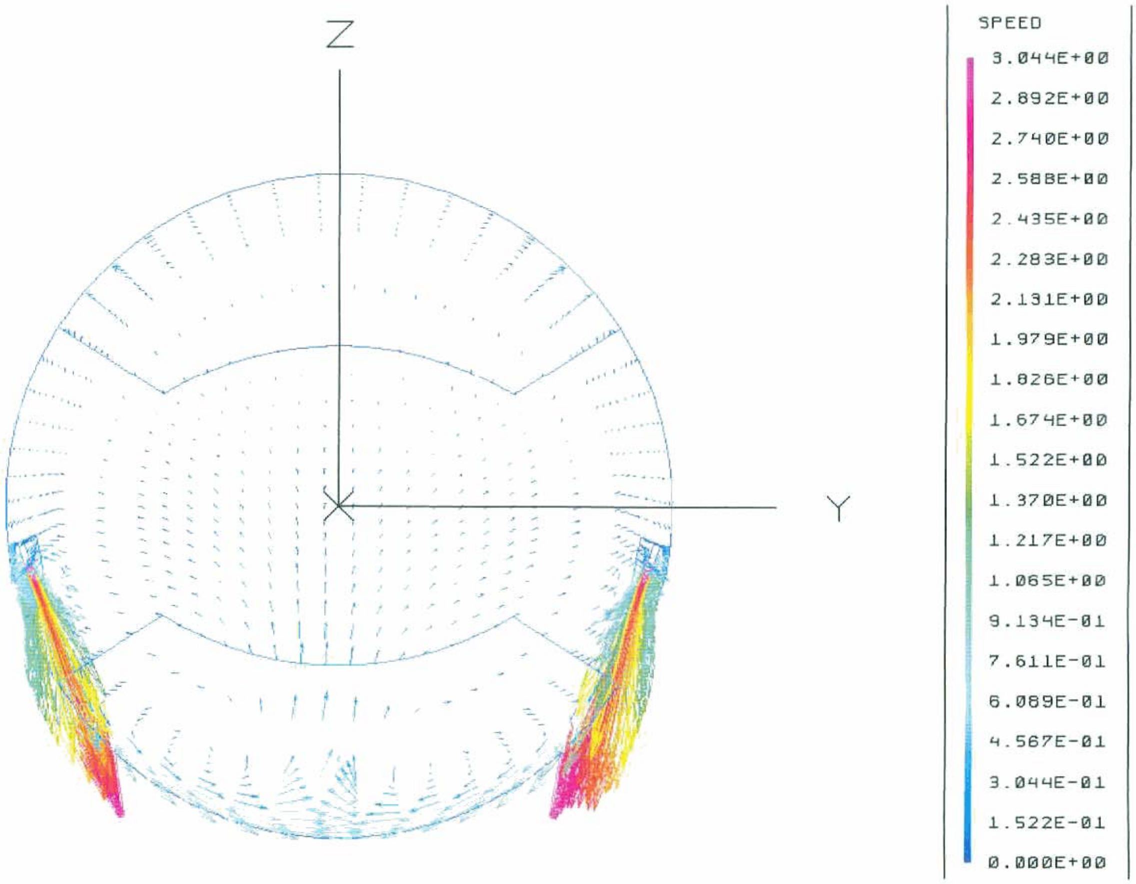

Figure 11a: Steady-State Velocity Vector Plot for the Modified C6 Geometry in a Nozzle Plane (Reference Case).

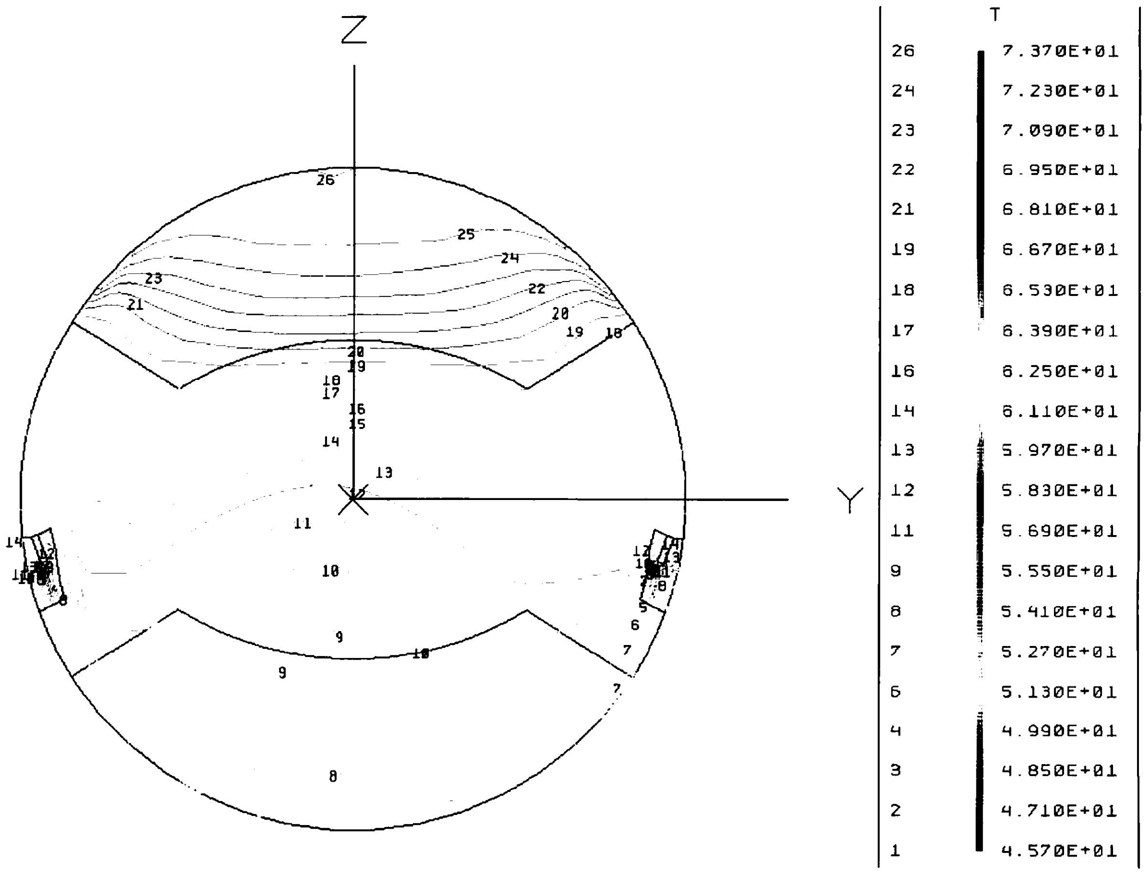

Figure 11b: Steady-State Temperature Contour for the Modified C6 Geometry at a Nozzle Plane (Reference Case).

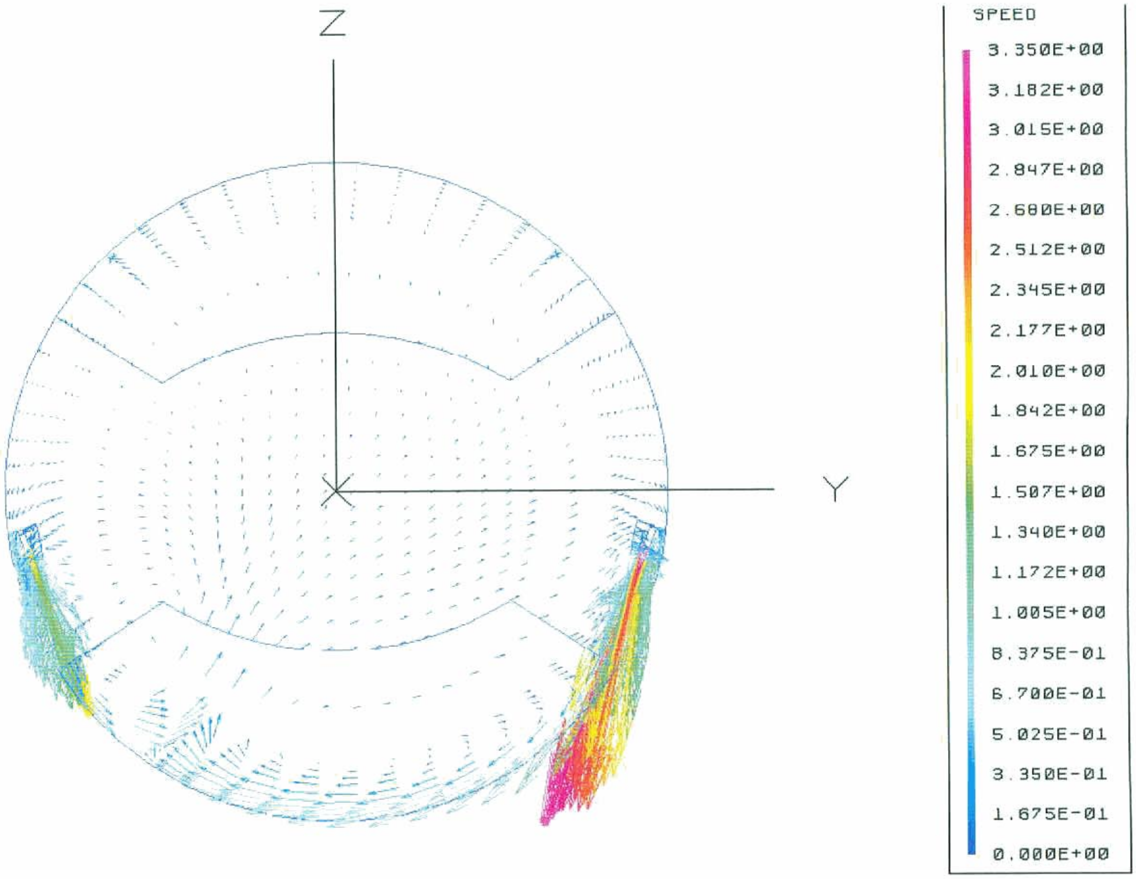

Figure 12a: Steady-State Velocity Vector Plot for the Modified C6 Design in a Nozzle Plane (Mass Flow Imbalance Case 2).

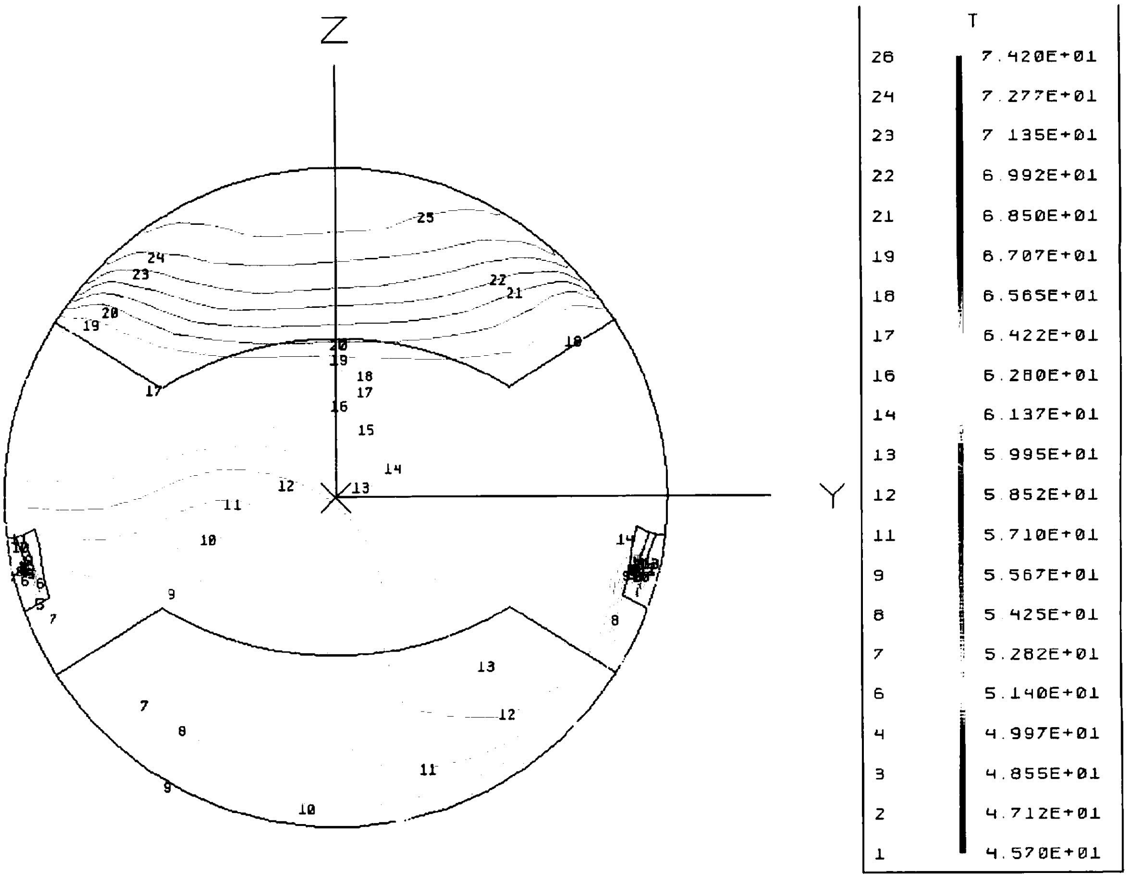

Figure 12b: Steady-State Temperature Contour for the Modified C6 Design in a Nozzle Plane (Mass Flow Imbalance Case 2).