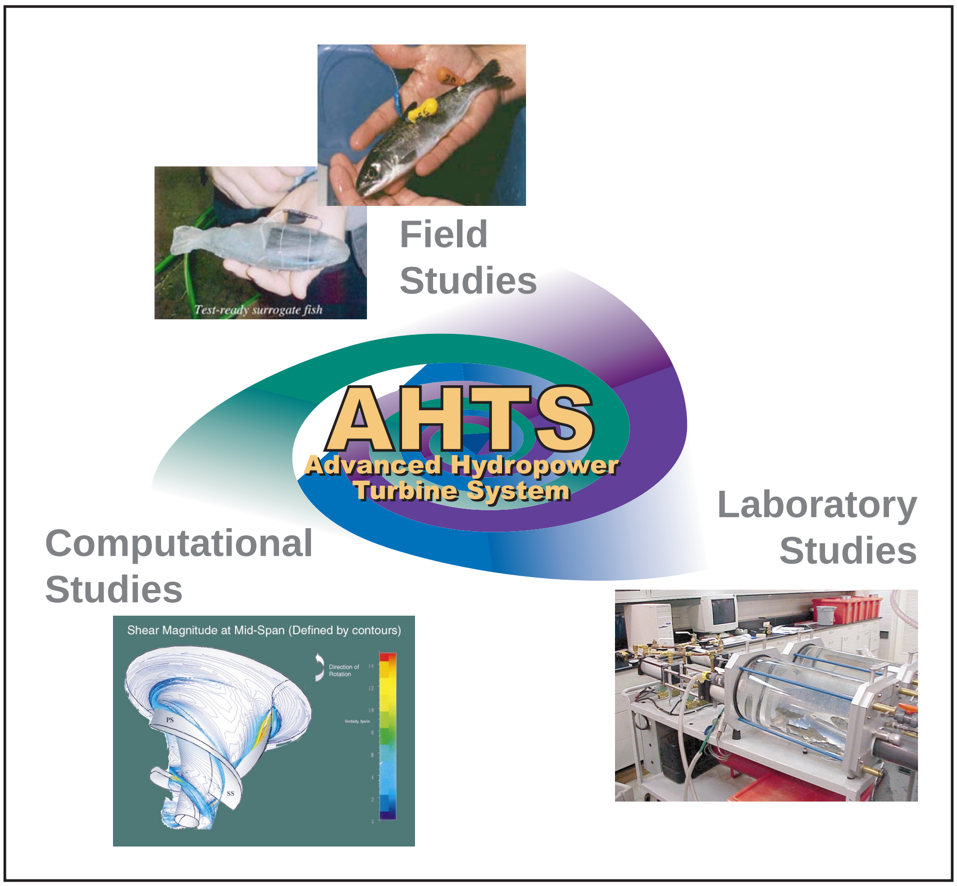
DOE/ID-10821

Final Turbine and Test Facility Design Report
Alden/NREC Fish Friendly Turbine



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United States
Department of Energy

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Final Turbine and Test Facility Design Report
Alden/NREC Fish Friendly Turbine

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FINAL REPORT
ALDEN/NREC FISH FRIENDLY TURBINE
DOE ADVANCED HYDRO-POWER TURBINE SYSTEM

FINAL TURBINE AND TEST FACILITY DESIGN

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FINAL TURBINE AND TEST FACILITY DESIGN

1.0 INTRODUCTION

1.1 SUMMARY OF PILOT SCALE STUDY

Alden Research Laboratory, Inc. (Alden) and Northern Research and Engineering Corporation (NREC) are conducting a research program to develop a new turbine runner to substantially reduce fish mortality at hydroelectric projects. Conceptual design of the turbine, previously conducted as part of the Advanced Hydropower Turbine Project sponsored by the U.S. Department of Energy (DOE), defined a new hydro-turbine runner with a unique geometry (U.S. Patent No. 5,997,242) that meets criteria that should allow safe passage of fish through the runner, while achieving a competitive hydraulic power efficiency (Cook, et al., 1997). The DOE then contracted Alden/NREC to refine the runner geometry and to design a pilot scale test facility that will be used to quantify the effect on fish passing through the turbine and verify the basic hydraulic characteristics of the turbine.

The main objective of the pilot scale turbine tests is to quantify the effects of the turbine on fish which pass through it. This will be accomplished by comparing the injury and survival rates of fish released upstream of the turbine (treatment groups) with that of control fish introduced in the same way downstream of the turbine. Handling and collection techniques will be designed to minimize the potential for stress and/or injury in order to provide the most accurate assessment possible of the small expected effects of passage through the turbine. Any observable injuries among treatment and control fish will be documented and survival will be evaluated over a four-day period following testing. Visualization of flow and fish passage will be recorded and attempts will be made to correlate the type of fish injury, if any, to turbine/runner features to identify possible future improvements to the runner. Actual runner improvements are, however, not envisioned.

If the difference in injury and mortality between the treatment and control fish is sufficiently small (i.e., there is negligible injury due to turbine passage), efforts will be directed toward the second objective, which is to measure the hydraulic characteristics of the turbine. Water-to-shaft power efficiency, local pressures, and velocities will be measured for comparison to the CFD analyses and for correlation to any observed fish injury. Tests for the onset of cavitation will not be possible due to facility constraints and are not of interest due to the high absolute pressures within the runner in actual applications.

Some power efficiency measurements will also be made prior to testing with fish to define the Best Efficiency Point (BEP). For a particular turbine, the BEP is that combination of head, speed and gate opening which produces the maximum efficiency.

The pilot scale turbine and test loop will be located within an existing Alden building. The test facility will be a closed flow loop with a pump, fish injection system, pilot scale turbine, and fish collection system. The pilot scale turbine will consist of a scroll case, wicket gates, runner, shaft, dynamometer, and draft tube. The facility will include auxiliary systems for holding and examining fish, controlling water quality, and turbine performance monitoring.

1.2 OBJECTIVES OF DESIGN PHASE

The basic objectives of the design phase reported on herein were to conduct additional analyses on the turbine and runner and to provide a final design of the pilot scale test facility.

Refinement of the turbine was necessary since the original runner was designed without regard to size and did not include a scroll case to distribute flow around the periphery of the runner. Also, any further possible improvement to the hydraulic efficiency was to be made since this would make the turbine a more competitive product in the marketplace.

Final design of the pilot scale test facility included selection of all hardware, especially the main test loop pump, all instrumentation, piping, fish injection and retrieval systems, fish rearing and handling facilities, water quality monitoring equipment, electrical wiring and any changes which needed to be made to the site foundation and building to accommodate the test facility. A final cost for constructing the facility and conducting the planned tests was prepared to complete the design effort.

Since the test program has a major influence on the required facility components and design, considerable effort was devoted to developing the program for biological (fish) and engineering tests.

1.3 OVERVIEW OF DESIGN PHASE

This report concludes the design phase for the turbine and pilot scale test facility, as well as a preliminary feasibility study to apply the new turbine to an existing Columbia River project (the John Day Project). Also completed is the program for biological and engineering tests, although some changes in the test program may occur with time, especially as early test results become available.

Future efforts will cover construction of the test facility, including a pilot scale turbine (with a four foot runner diameter), and conducting both the biological (fish) and engineering tests.

This report summarizes the second phase of the turbine design, leading to a refinement of the runner shape and design of the scroll case and wicket gates, describes the final design of the test loop and auxiliary equipment, provides details of the test program, and gives a summary of the cost estimate for various aspects of the work.

The turbine design is covered in Section 2.0, followed by a description of the test loop design and features in Section 3. Both the biological and engineering test programs are covered in some detail in Section 4.0. Cost estimates are provided in Section 5.0 for completing the pilot scale study, including the procurement of needed equipment and subcontract services for fabrication and installation of the test facility components. Section 6.0 presents the proposed schedule for completing the test facility and evaluating the new turbine performance. An application of the new turbine to the John Day Project is provided in Section 7.0.

2.0 TURBINE DESIGN

The Phase 1 conceptual design considered only the runner and was based on the assumption that the non-rotating inlet portion (scroll case) of the turbine flow path could later be designed to achieve the inlet conditions calculated in Phase 1 based on conservation of angular momentum. In addition, flow control devices, such as wicket gates, were not considered in the Phase1 conceptual design of the runner. Three-dimensional analysis of the scroll case (with and without wicket gates) was conducted to determine the approach flow angle to the blade's leading edges. Three-dimensional (CFD) analysis of the runner was being conducted almost simultaneously to maintain the schedule, assuming the same inlet conditions as for the Phase 1 runner design. Therefore, design of the scroll was based on achieving this same inlet condition. A vaneless nozzle between the wicket gate end and the runner inlet is used to start turning the flow downward to achieve the desired mixed inflow to the runner.

2.1 SCROLL CASE DESIGN

The pilot scale turbine was developed from the full size unit which had a design point of 1,000 cfs and 85 ft head, resulting in a runner diameter of 13 ft. The sizing of the pilot scale turbine was based in part on providing flow passages large enough for meaningful testing of available fish species; the minimum allowable flow passage within the scroll and runner was chosen to be about 6 inches by 6 inches. The pilot turbine is designed to operate at the full size turbine gross head of 85 ft. Together with the available flow capacity of the test loop at this head, the minimum clearance resulted in a pilot scale runner diameter of 4 ft. These factors lead to the following scroll case design parameters:

- Geometric scaling is 3.25 to 1 (13 ft to 4 ft)
- Pilot scale flow is 95 cfs
- Number of wicket gates is 11

The 3.25:1 scale pilot runner entrance opening is slightly greater at 6-7/8 inches than the design goal. In order to maintain a minimum “square” passage through the wicket gates, 11 gates were chosen. Also, to avoid resonant interaction between the runner and the gates, the number of wicket gates (11) was selected to not be a multiple of the number of runner blades (3).

The shape of the scroll was derived with the goal of using a single scroll case with and without wicket gates installed. For this to work, the scroll must be designed to provide the desired velocity and angle at the runner entrance without gates and, when installed at BEP, the gates must not alter the streamlines established by the scroll. There must also be sufficient room to increase the gate opening from BEP, and the gates must be long enough to have sufficient overlap to guide the flow at off BEP positions and seal when closed.

The first step to designing the dual purpose scroll was to incorporate a region outside the entrance to the runner where the gates would be placed (allowing for opening the gates approximately 10 degrees beyond BEP). The second step involved adjusting the angular momentum in the scroll (average velocity times radius from scroll centerline) by changing the scroll entrance velocity (size of pipe) and radial location of the scroll relative to the runner. These adjustments were needed to overcome the effects of friction on the flow speed and direction entering the vaneless downturn and the runner, so that the design head of the runner would be achieved. The area reduction of the scroll was adjusted to establish a constant circumferential velocity and, thus, provide uniform flow around the circumference of the runner.

Numerical methods, described in following sections, were used to analyze the performance of several scroll geometries. These analyses included the effects of friction and geometry within the scroll and transition to the radial (horizontal) wicket gate space; a total of ten iterations of the scroll geometry were required to meet the entrance conditions assumed for the runner design. The final scroll without gates established the correct inlet velocity and area reduction schedule so that after the flow passed through the empty wicket gate area, its velocity and angular components matched those used to design the runner. Figure 2-1 shows the scroll with idealized streamlines through the wicket gate area.

Once a suitable scroll without gates was developed, the wicket gates were "installed" and the numerical analysis was repeated. In addition to maintaining the minimum flow passage through the wicket gates, it was desired to maintain sufficient overlap between gates in plan view, as shown in Figure 2-2, to provide adequate flow guidance at off design operation. This nozzle passage is generated by the length of the vanes placed along streamlines determined by the numerical analysis of the scroll without gates, as shown in Figure 2-2.

As described above, the single scroll design assumed that once the geometry without wicket gates was finalized, the wicket gates could be installed and aligned with the flow streamlines to minimize their effect on the flow patterns at BEP. Details of the design at BEP were based on the pilot scale flow of 95 cfs and included:

- establishing a flow angle of 69.5 degrees (±0.75 degrees) from radial at the entrance to the vaneless downturn nozzle,
- minimizing regions of flow separation at BEP (i.e., at the leading and trailing edges of the wicket gates), and , as a result,
- minimizing the head loss from scroll inlet to runner inlet.

In addition to these hydraulic criteria, the design of the scroll (including the shape and thickness of the wicket gates) was also influenced by structural requirements.

The preliminary analytical scroll design without wicket gates was based on the principals of conservation of angular momentum and did not include the effects of viscosity, turbulence and boundary surface characteristics on the flow. To evaluate the effects of these parameters on the flow through the scroll and to further refine the design, three-dimensional numerical simulations were performed using Computational Fluid Dynamics (CFD). CFD has been extensively used in hydroturbine component design and is particularly well suited for three dimensional scroll case analyses. For the present analysis, the CFD software FIDAP V8.5 was used to perform the flow simulations. FIDAP is a state-of-the-art fluid flow simulation suite with program modules for problem setup, boundary condition specification, and solution phases of a flow analysis. The computational mesh was developed using the program GAMBIT and solution analyses were performed using the FIELDVIEW post-processing software.

Problem setup included generation of a three dimensional computational grid (for scroll geometries with and without wicket gates) and specification of flow properties, boundary conditions and initial conditions. The commonly used k-ω model, modified for high Reynolds number flow, was used to simulate the effects of turbulence. Boundary conditions included a uniform inlet velocity distribution with an average magnitude of 13.9 ft/s and a uniform pressure distribution at the entrance to the runner. The no-slip condition was applied along all solid surfaces with an absolute roughness height equivalent to that of steel plate.

Simulations of the scroll without wicket gates were performed first followed by simulations of the scroll with wicket gates.

2.1.1 Scroll Case Without Wicket Gates

The computational mesh for the scroll case without wicket gates is shown in Figure 2-3. A structured meshing scheme was used in the direction of the flow whereas an unstructured mesh was created in the cross sectional direction to resolve boundary layer effects. After completing a sensitivity analysis, it was determined that a total of 279,000 elements were required to obtain a grid independent solution. A series of simulations were performed to arrive at the final scroll design which satisfied the aforementioned design criteria at BEP.

Figure 2-4 shows the velocity distribution across the horizontal mid plane of the scroll. Note the uniformity of the flow around the circumference and the expected acceleration of the flow towards the runner inlet. The velocity distribution along four vertical planes is shown in Figure 2-5. Note that the flow is symmetric about the centerline of the cross section and that the flow is accelerated uniformly through the radial space and vaneless downturn. The meridionally averaged velocity distribution at the entrance to the vaneless downturn is shown in Figure 2-6. Note that the meridionally averaged flow magnitude around the periphery of the scroll is very constant and that the circumferentially averaged vertical (meridional) velocity profile is nearly linear. The effect of the wake created by the tongue is evident at an angle of approximately 45 degrees. The average meridional flow angle distribution (angle measured off radial) is shown in Figure 2-7. For the final selected scroll design, the average angle is 70.1 degrees, which is within the desired range of 69.5 degrees to ±0.75 degrees. Figure 2-8 shows the three dimensional flow streamlines at BEP. Head loss through the scroll without any gates was determined to be approximately 1.8 ft.

Once the final scroll design without wicket gates had been completed, an analysis was performed with the wicket gates in place (initially aligned with the BEP flow streamlines) to determine their influence, if any, on the flow through the scroll.

2.1.2 Scroll Case With Wicket Gates

The computational mesh for the scroll case with the 11 wicket gates installed is shown in Figures 2-9 and 2-10. The wicket gates were initially aligned with the flow streamlines calculated in the previous simulation (without wicket gates) to minimize their effect on the flow patterns in the scroll. A structured meshing scheme was used in the direction of the flow whereas an unstructured mesh was created in the cross-sectional direction to resolve boundary layer effects. A concentration of rectangular elements were placed along each wicket gate to properly model the flow along the gate surface. After completing a sensitivity analysis it was determined that a total of 578,000 elements were required to obtain a grid independent solution.

A series of simulations were performed to arrive at the final scroll design which satisfied the aforementioned design criteria at BEP. It was determined that the 11 gates did slightly influence flow patterns as the gate blockage caused higher velocities and more tangential flow angles. Consequently, the length of the gates was slightly reduced and the gates were turned about four degrees farther open to achieve the more radial design inflow conditions for the runner at BEP.

Figure 2-11 shows the velocity distribution across the horizontal mid plane of the scroll. Note the uniformity of the flow around the circumference and the expected acceleration of the flow through the gates towards the runner inlet. Local accelerations between the gates are also evident with gate wake effects extending downstream of the trailing edge of each gate. Figure 2-12 shows a detail of the velocity field between two consecutive gates. Note that the approach flow nearly bisects the leading edge of the gate and that there is no appreciable flow separation immediately downstream of the gate trailing edge. The average meridional velocity distribution at the entrance to the vaneless downturn is shown in Figure 2-13. The circumferentially averaged vertical velocity profile is parabolic and the average flow magnitude around the periphery of the scroll clearly shows the individual gate wakes. However, the effect of the wake created by the tongue is barely evident between the angles of 45 to 50 degrees since that wake was aligned with a gate, see Figure 2-13. The average meridional flow angle distribution (angle measured off radial) is shown in Figure 2-14. Again, the affect of the wicket gates on the local flow angles is evident. However, for the final selected design, the average angle is 69.9 degrees which is within the desired range of 69.5 degrees to ±0.75 degrees. Figure 2-15 shows the three dimensional flow streamlines at BEP. The head loss through the scroll with the wicket gates installed is 2.2 ft.

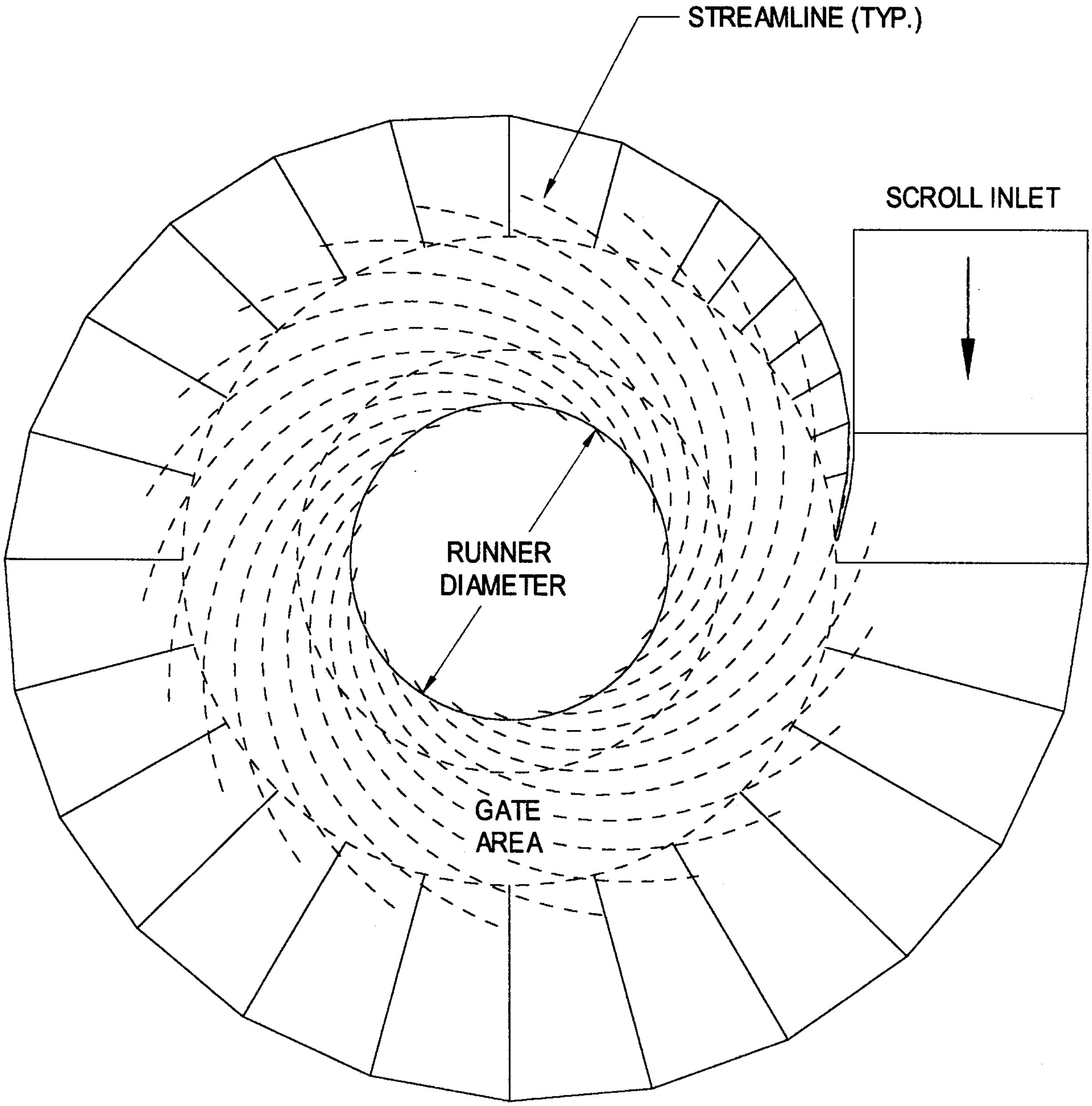


FIGURE 2-1 PLAN OF SCROLL SHOWING IDEALIZED STREAMLINES
THROUGH WICKET GATE AREA

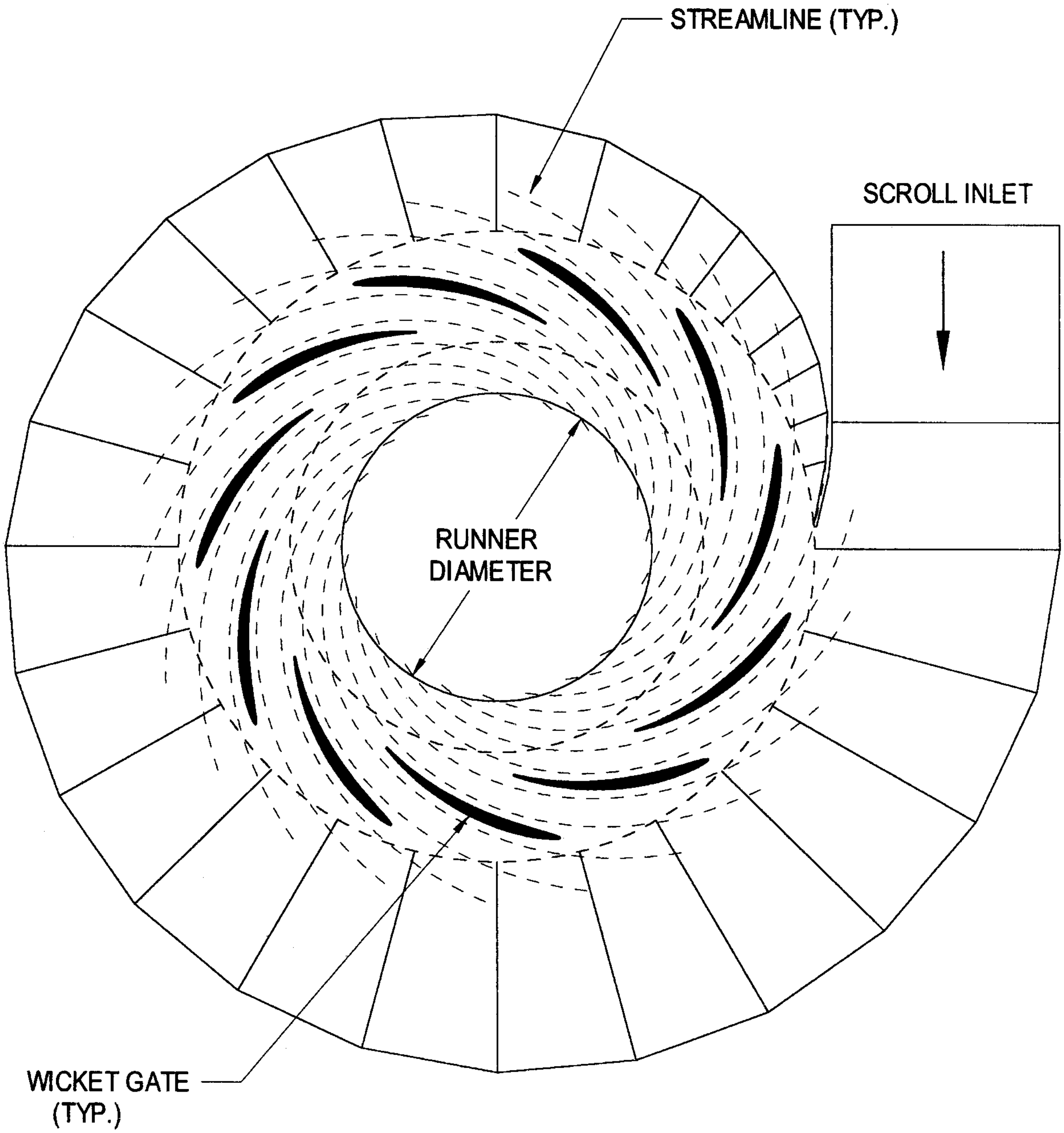


FIGURE 2-2 PLAN OF SCROLL SHOWING WICKET GATES ALIGNED TO FLOW STREAMLINES

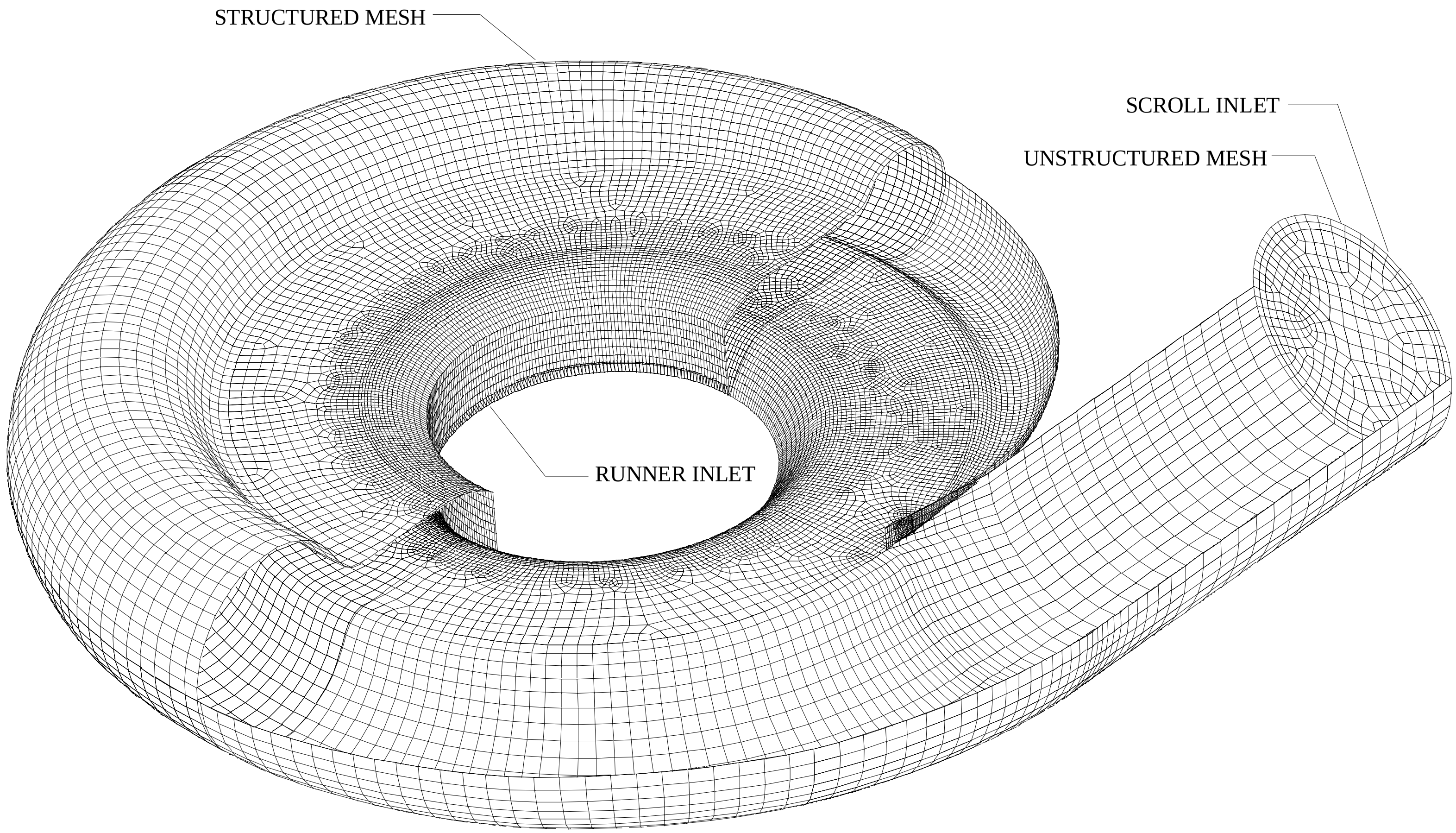


FIGURE 2-3 SCROLL CASE DESIGN WITHOUT WICKET GATES - COMPUTATIONAL MESH

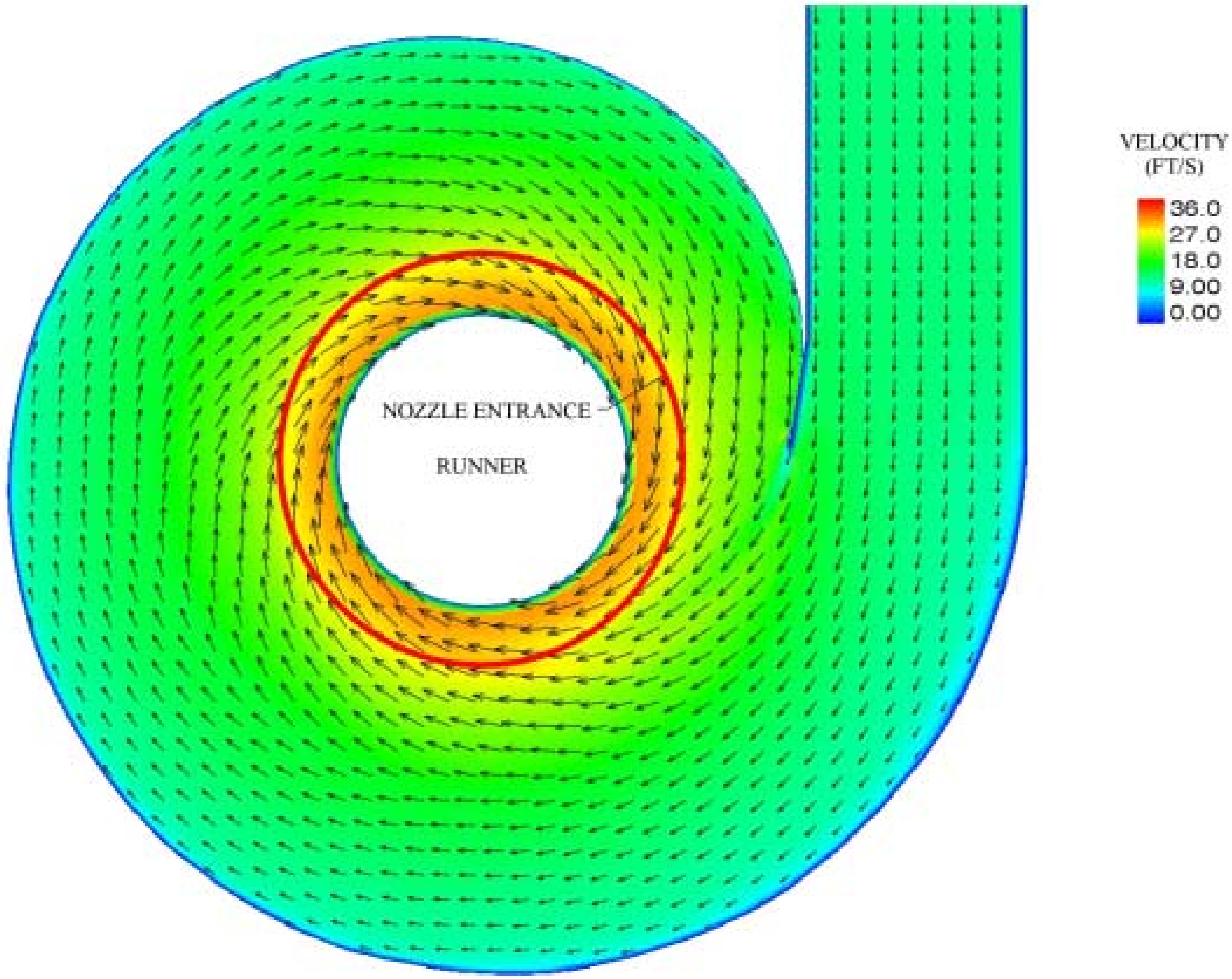


FIGURE 2-4 SCROLL CASE DESIGN WITHOUT WICKET GATES - VELOCITY DISTRIBUTION AT MID PLANE

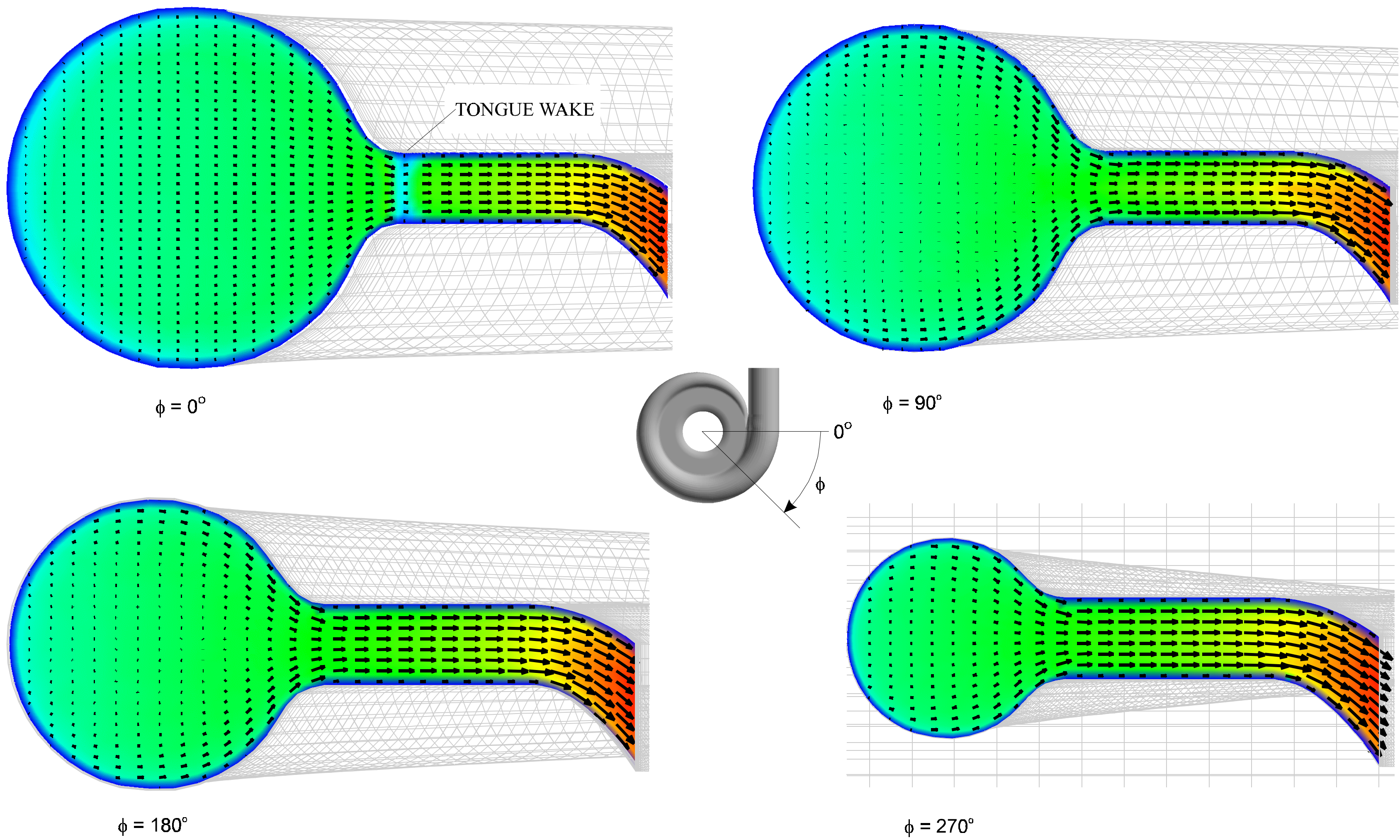
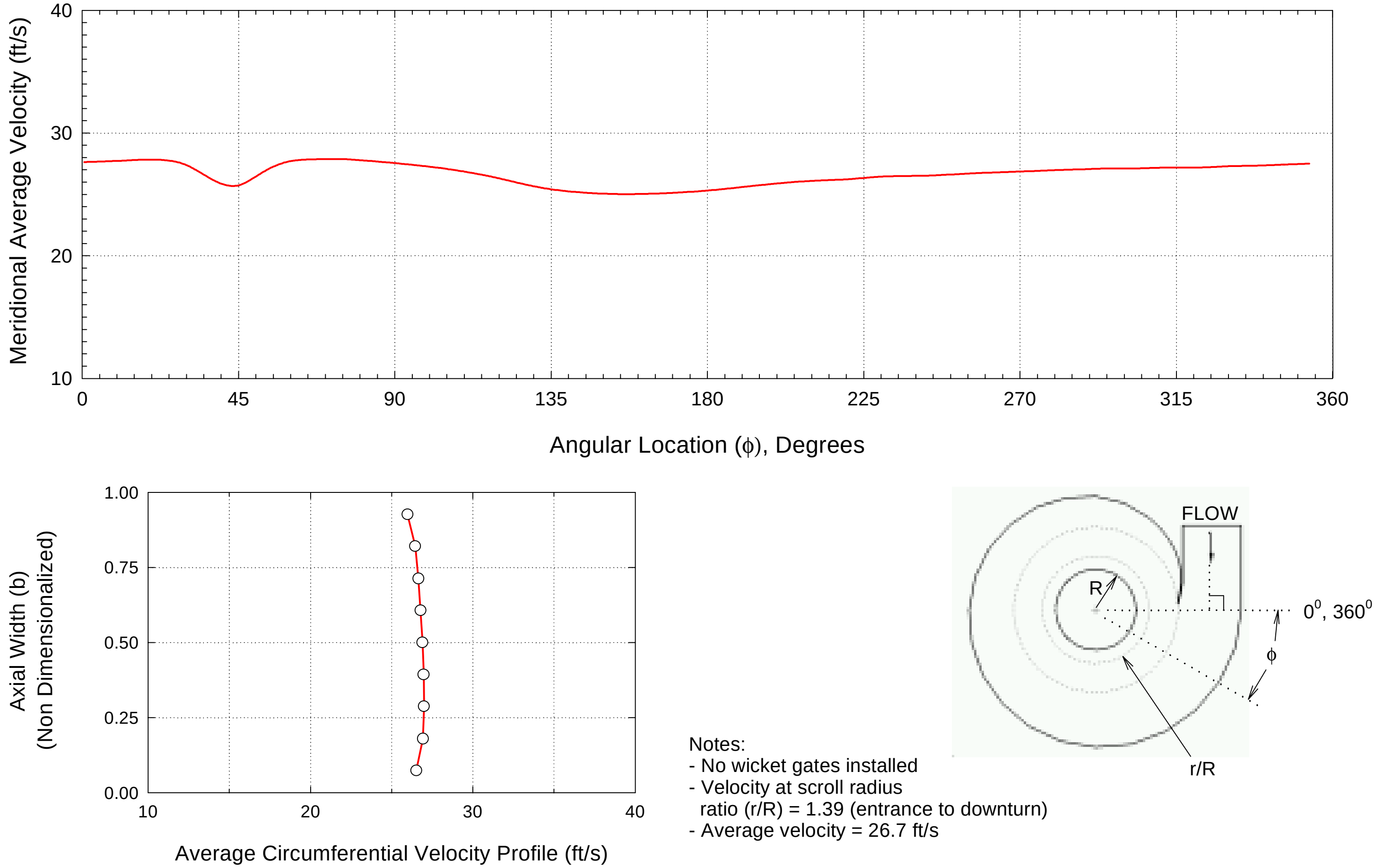
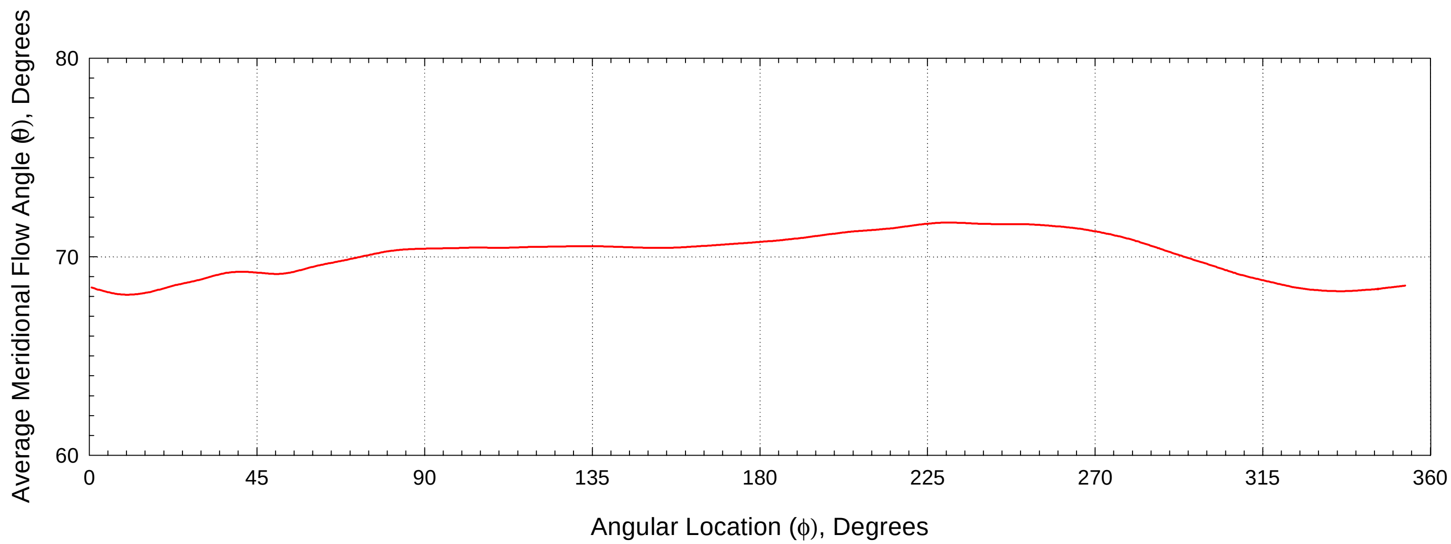


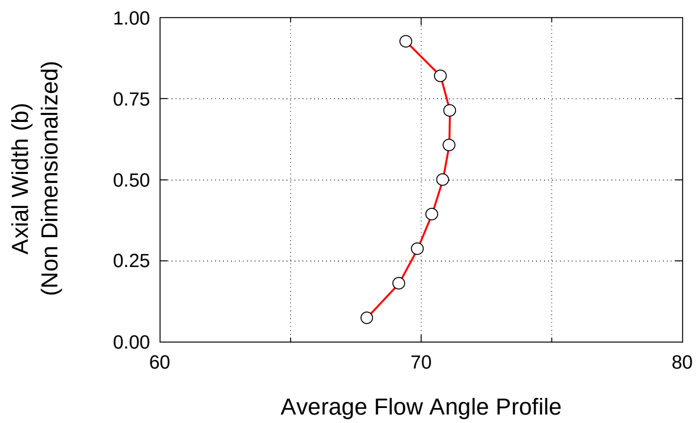
FIGURE 2-5 SCROLL CASE DESIGN WITHOUT WICKET GATES - VELOCITY DISTRIBUTION ALONG CONSECUTIVE VERTICAL PLANES

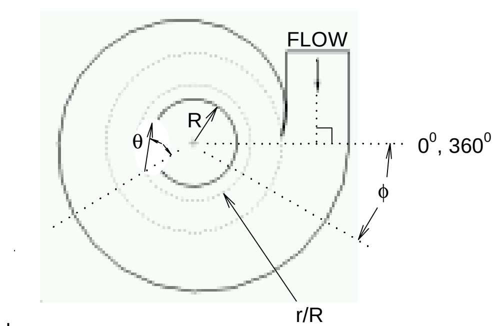


Notes:
- No wicket gates installed
- Velocity at scroll radius ratio (r/R) = 1.39 (entrance to downturn)
- Average velocity = 26.7 ft/s

FIGURE 2-6 AVERAGE VELOCITY DISTRIBUTION AT ENTRANCE TO DOWNTURN WITHOUT WICKET GATES







Notes:
- No wicket gates installed
- Values at scroll radius ratio = 1.39 (entrance to downturn)
- Average angle (θ) = 70.1 degrees

FIGURE 2-7 AVERAGE ANGULAR DISTRIBUTION AT ENTRANCE TO DOWNTURN WITHOUT WICKET GATES

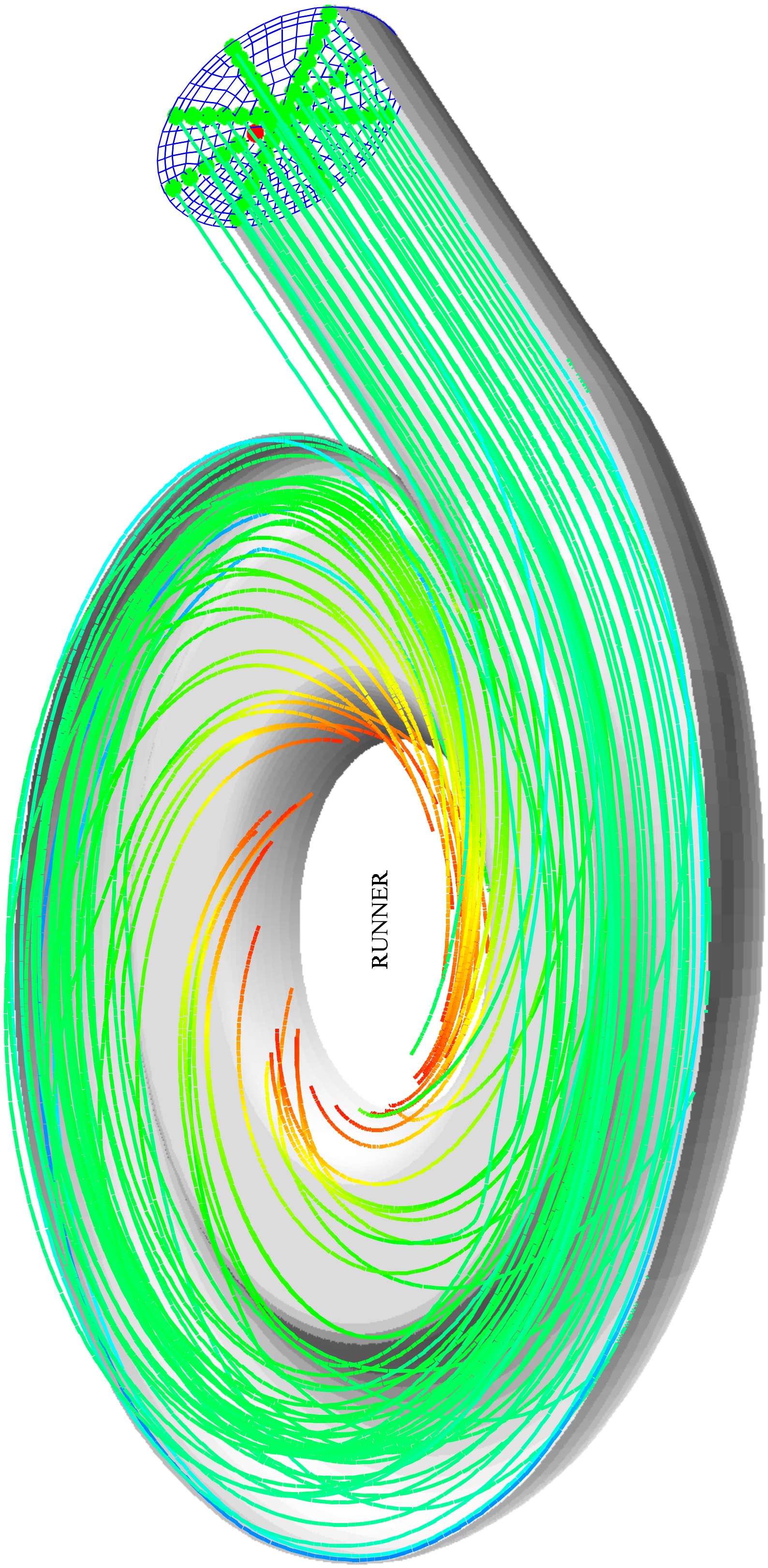


FIGURE 2-8 SCROLL CASE DESIGN WITHOUT WICKET GATES - STREAMLINE CONTOURS

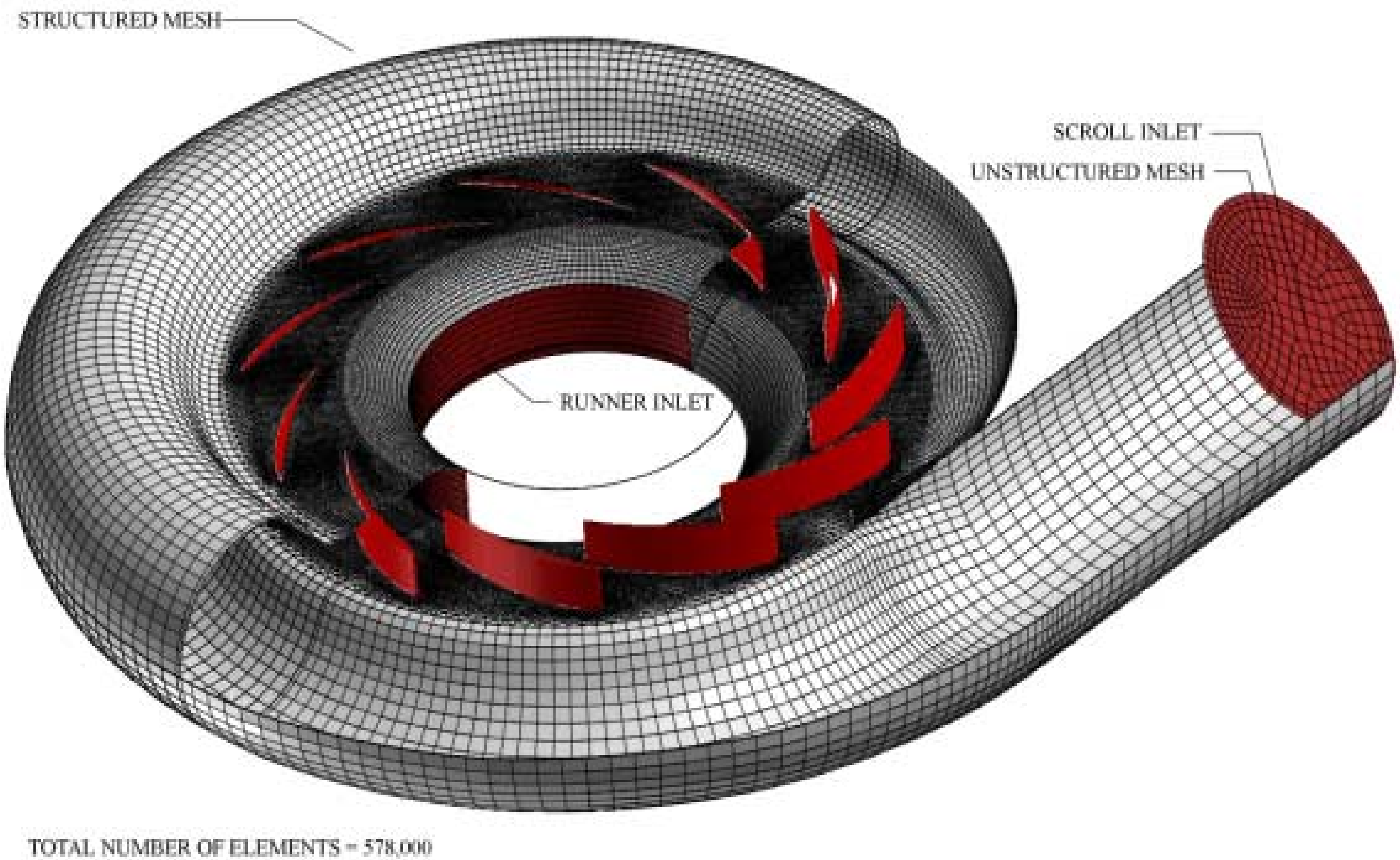


FIGURE 2-9 SCROLL CASE DESIGN WITH WICKET GATES - COMPUTATIONAL MESH

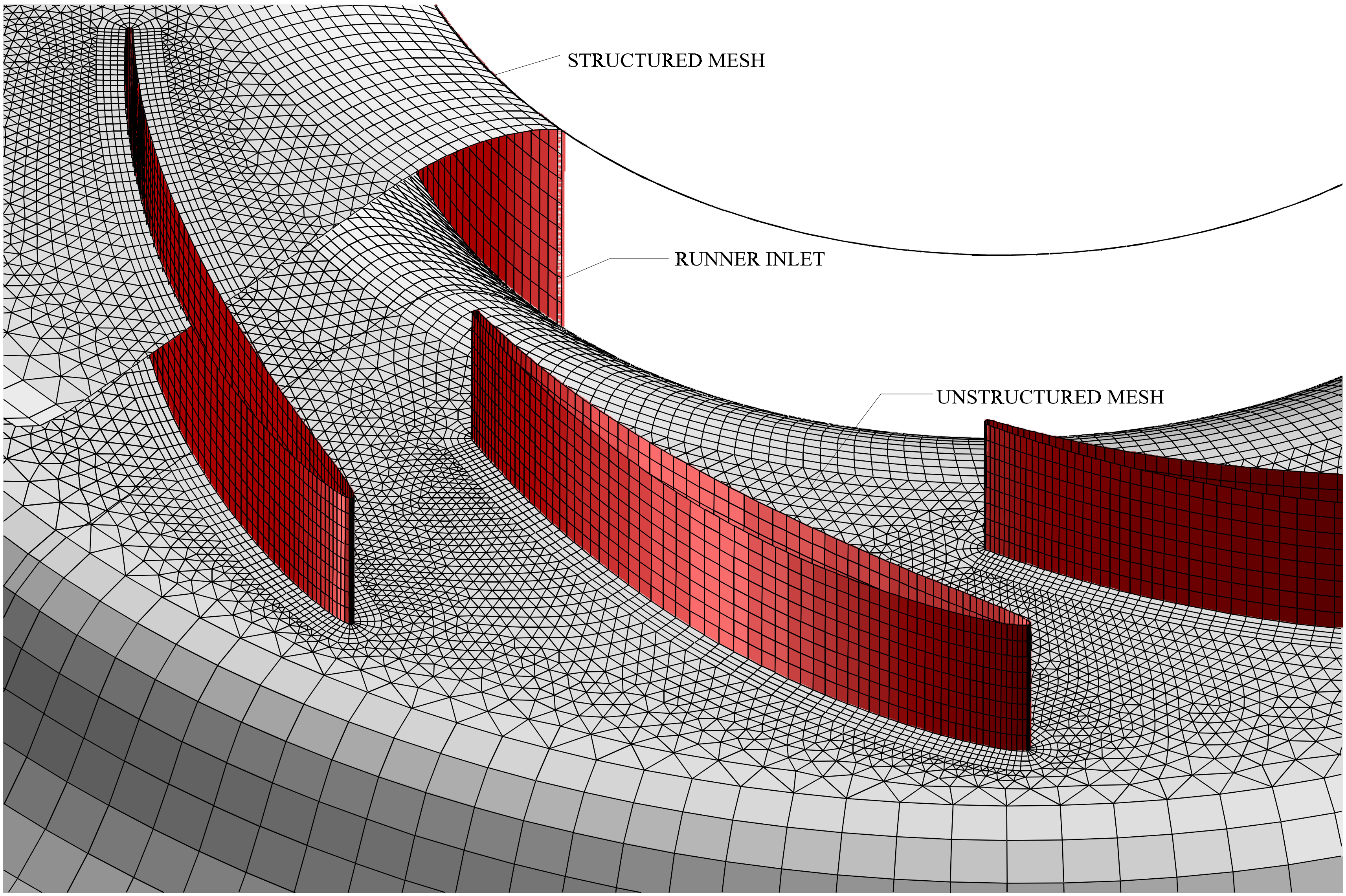


FIGURE 2-10 SCROLL CASE DESIGN WITH WICKET GATES - COMPUTATIONAL MESH NEAR GATES

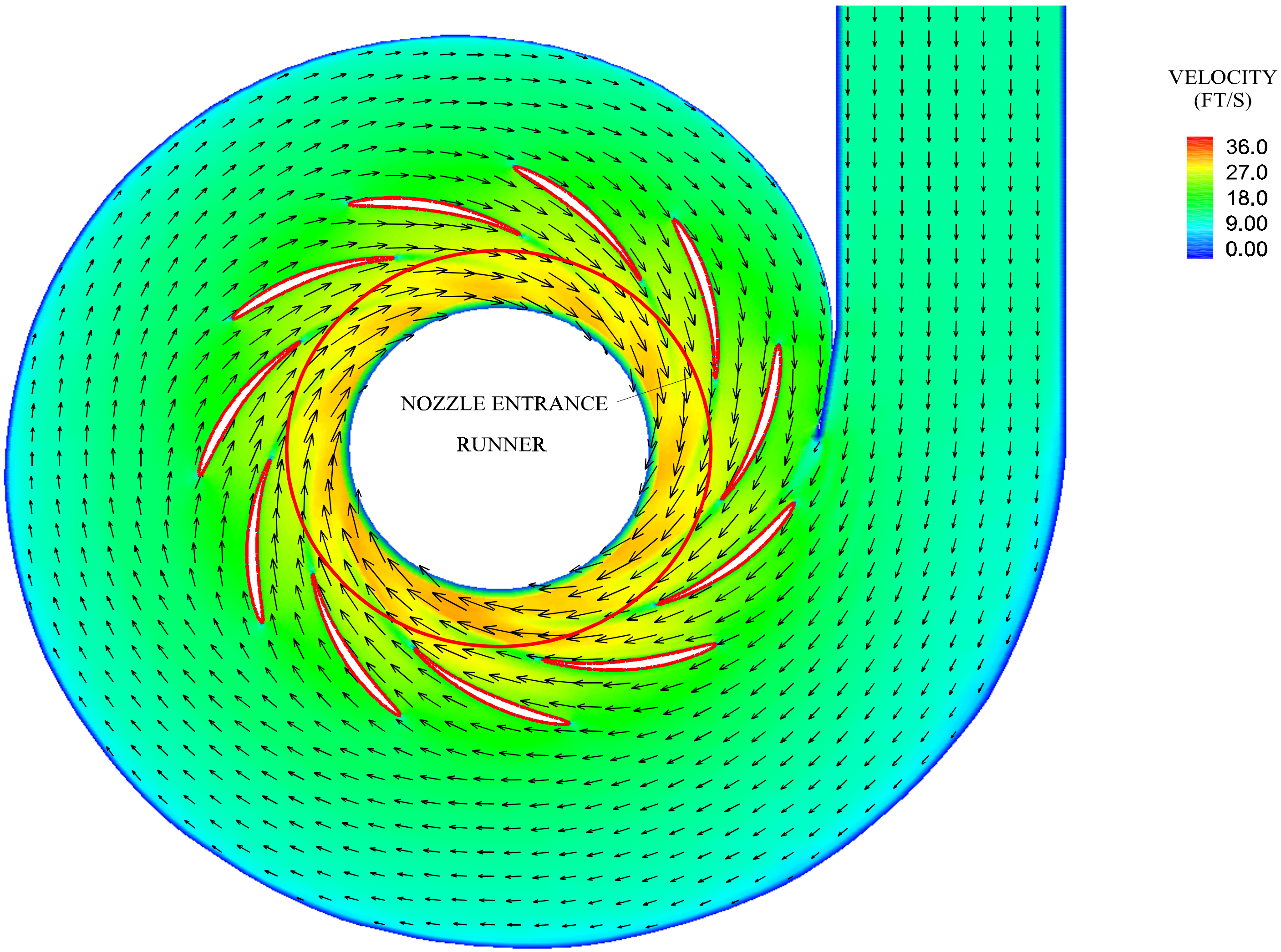


FIGURE 2-11 SCROLL CASE DESIGN WITH WICKET GATES - VELOCT8Y DISTRIBUTION AT MID PLANE

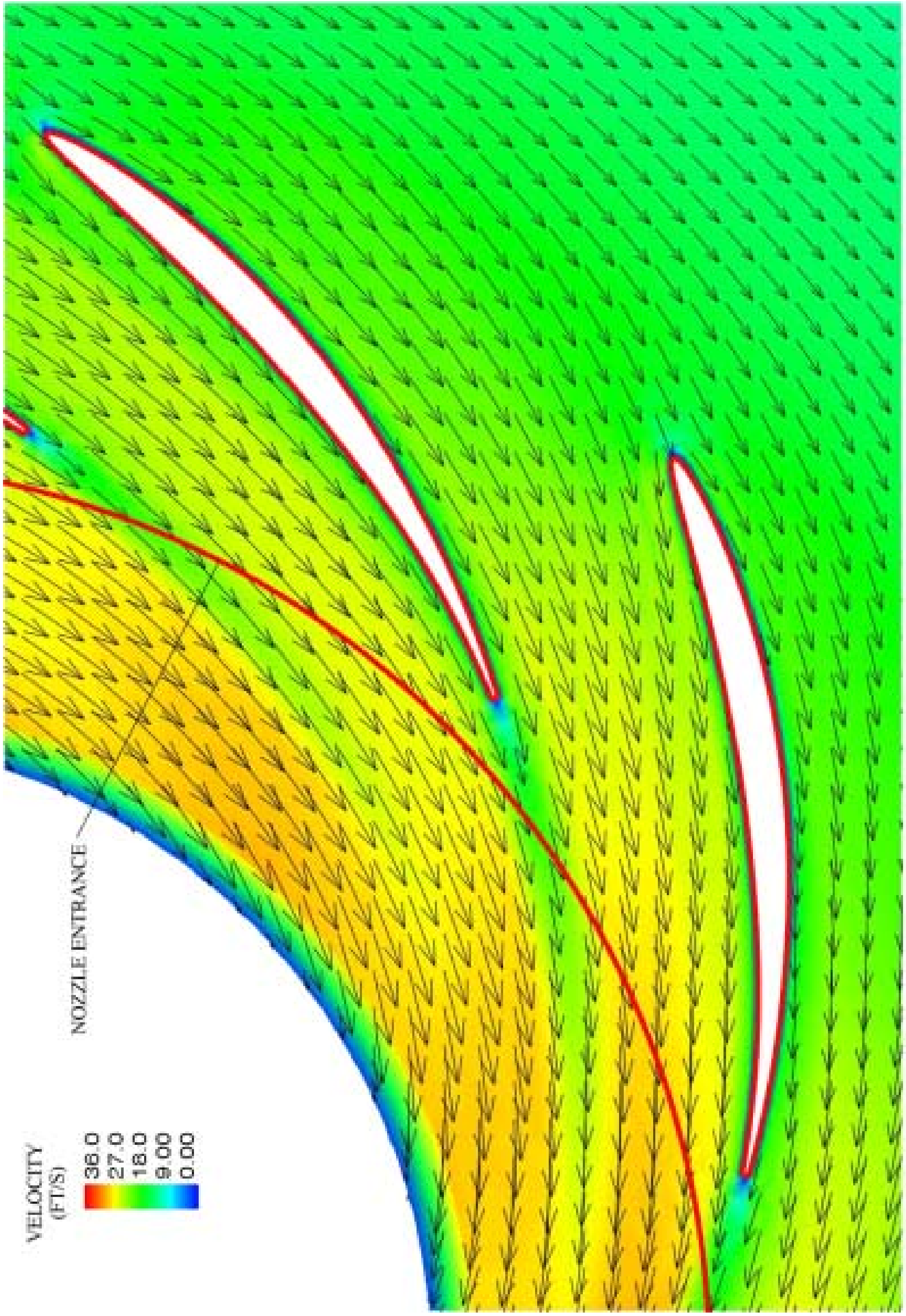
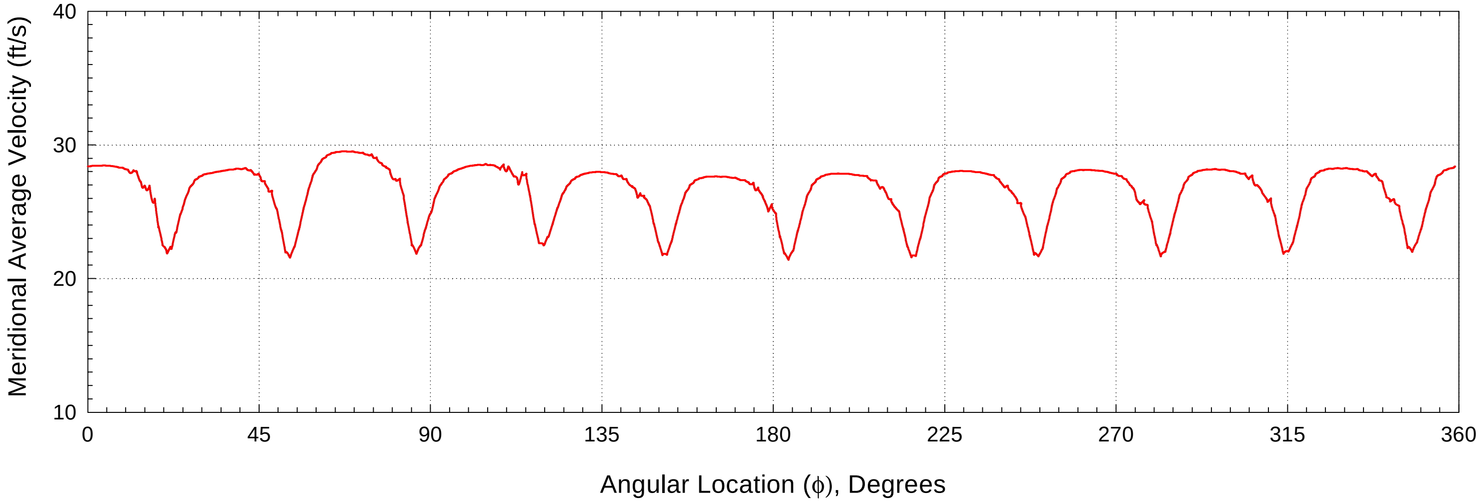
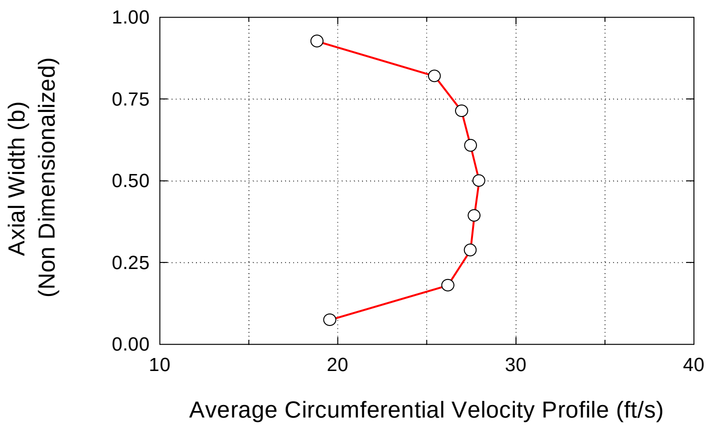
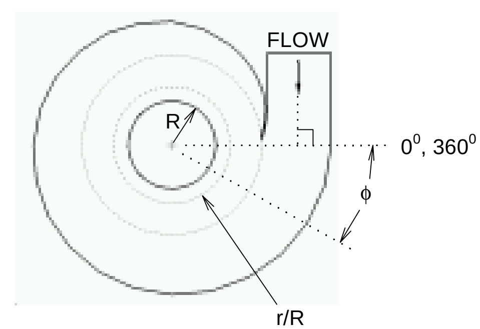


FIGURE 2-12 SCROLL CASE DESIGN WITH WICKET GATES - VELOCITY DISTRIBUTION
AT MID PLANE BETWEEN TWO WICKET GATES

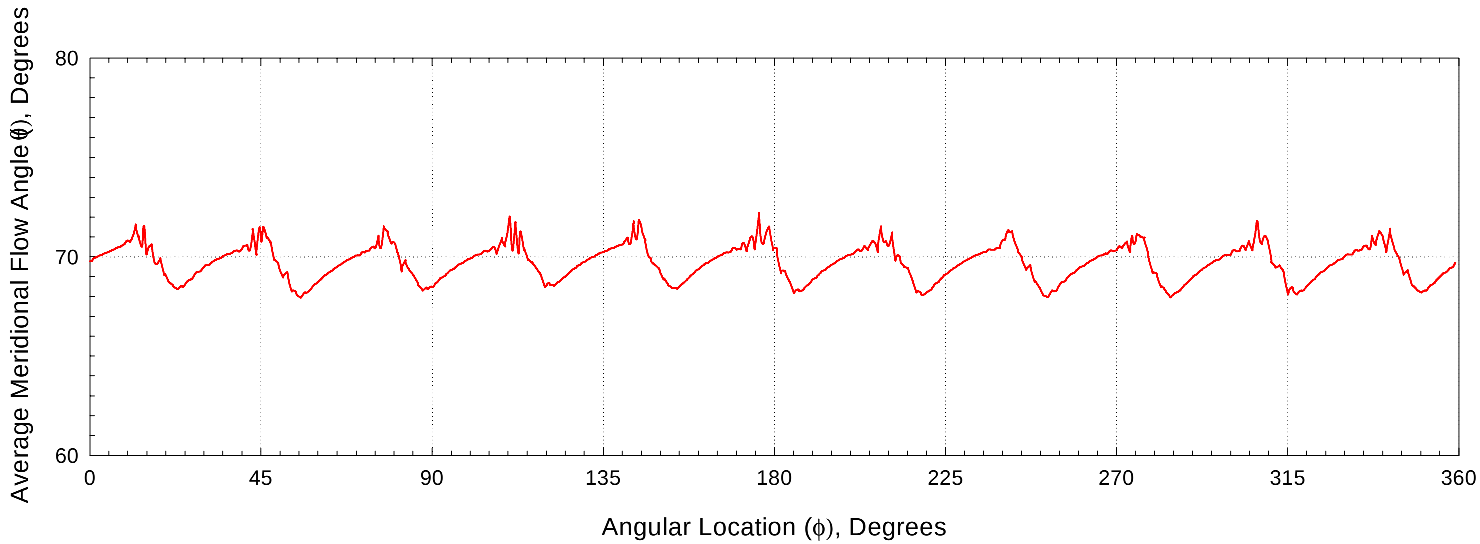


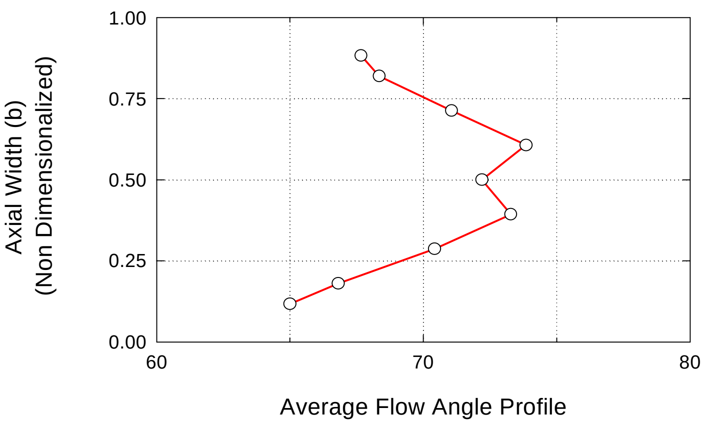


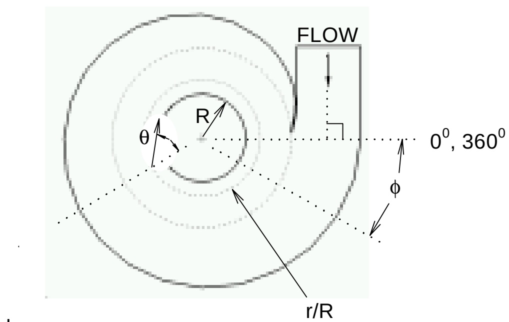


Notes:
- 11 wicket gates installed
- Velocity at scroll radius ratio (r/R) = 1.39 (entrance to downturn)
- Average velocity = 26.7 ft/s

FIGURE 2-13 AVERAGE VELOCITY DISTRIBUTION AT ENTRANCE TO DOWNTURN WITH WICKET GATES







Notes:
- 11 wicket gates installed
- Values at scroll radius ratio = 1.39 (entrance to downturn)
- Average angle (θ) = 69.8 degrees

FIGURE 2-14 AVERAGE ANGULAR DISTRIBUTION AT ENTRANCE TO DOWNTURN WITH WICKET GATES

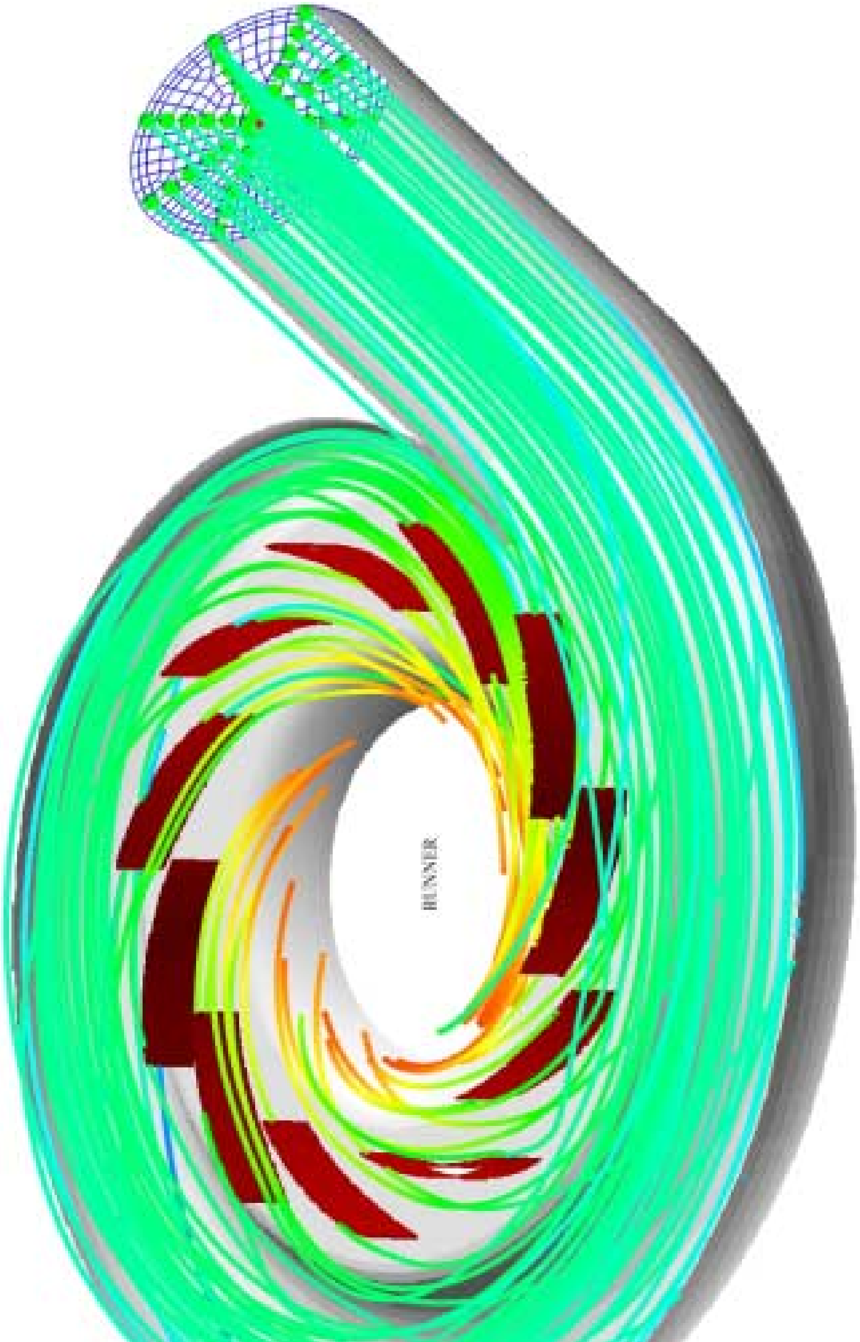


FIGURE 2-15 SCROLL CASE DESIGN WITH WICKET GATES - STREAMLINE CONTOURS