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Flow Simulation in Secondary Flow Passages of a Rocket Engine Turbopump

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ABSTRACT

This paper presents application of a Generalized Fluid System Simulation Program, GFSSP to model fluid flow in a very complex secondary flow circuit of a rocket engine turbopump, SIMPLEX. SIMPLEX was a low cost turbopump designed, manufactured and tested to demonstrate the ability to reduce the overall cost and design cycle time of turbomachinery. GFSSP is a general purpose computer program for analyzing flowrate, pressure, temperature and concentration distribution in a complex flow network. The program employs a finite volume formulation of mass, momentum and energy conservation equations in conjunction with thermodynamic equation of state of a real fluid. The secondary flow passages modeled include flow between the impeller shroud and housing, impeller back face and housing, flow through labyrinth seal and bearing, return line flow to inducer and flow adjacent to front and back face of the turbine. Axial load on the bearing are calculated from the predicted pressure on all axial faces of the rotor. The predicted pressure and temperature distributions compared well with the test data.

1.0 BACKGROUND

A simple, low cost turbopump, named SIMPLEX was designed, manufactured and tested at NASA's Marshall Space Flight Center (MSFC) to demonstrate the ability to reduce the overall cost and design cycle time of turbomachinery. The main objectives of this turbopump were to minimize part complexity and reduce design and analysis time. This task was accomplished by multi-disciplinary design and analysis effort which included CFD, stress analysis, structural dynamics, rotordynamics, thermal, thrust balance and secondary flows[1]. The axial thrust balance and secondary flow model was developed by Van Hooser[2] using a secondary flow analysis code developed by Cheng[3] for the Space Shuttle Main Engine Turbopump analysis. The model included the bearing coolant flow, front face impeller recirculation flow, and the seal drain flow. An estimate of the pressure along all axial faces of the rotor was used to calculate the axial force from the pump and turbine such that the net force does not exceed the bearing capability. Since the model did not include rotational effect, the results from CFD analysis was used to compute net axial thrust. Secondary flows were adjusted to minimize the net axial force on the rotor and to ensure an adequate coolant flow for the bearings.

During the design of SIMPLEX, it was realized that the development of a secondary flow model for a new design using a specific purpose code was time consuming and inefficient. To satisfy the need to model a new turbopump, a general purpose flow network code capable of modeling phase change, rotational and compressibility effects was developed[4]. The code called Generalized Fluid System Simulation Program (GFSSP) was verified by comparing its predictions with two commercially available codes[5]. The purpose of this investigation was to develop an integrated model of the SIMPLEX turbopump using GFSSP to compute the secondary flow distribution and axial thrust. The model results were compared with the test data.

2.0 SIMPLEX TURBOPUMP

The SIMPLEX turbopump is shown schematically in Figure 2.1. The secondary flow passages modeled include:

1. Axial flow between the impeller shroud and the housing flowing from the impeller discharge,
2. Radially inward flow between the impeller shroud and the housing,
3. Flow through the Labyrinth Seal at the end of the impeller shroud,
4. Radially inward flow between the end of the impeller shroud and the housing flowing into the impeller inlet,
5. Axial flow between the impeller and the housing flowing from the impeller discharge,
6. Radially inward flow between the impeller back face and the housing,
7. Flow through the Labyrinth Seal at the lip on the back face of the impeller,
8. Radially inward flow between the impeller back face and the housing flowing into the first bearing,
9. Flow through the first rolling element bearing,
10. Axial flow along the impeller shaft between the bearings,
11. Flow through the second rolling element bearing,
12. Flow through eight radially outward holes (for return lines),
13. Flow through two external return lines,
14. Flow through eight radially inward holes flowing into inducer inlet,
15. Flow through the first turbine-end Labyrinth Seal,
16. Flow through twenty two radially outward holes (for dump lines),
17. Flow through two external dump lines,
18. Flow through the second turbine-end Labyrinth Seal,
19. Radially outward flow between the front face of the turbine and the housing.

Additionally, a dummy circuit connects the front face and the back face of the turbine for the calculation of axial thrust.

The above listed passages are identified in Figure 2.1.

3.0 GFSSP MODEL

GFSSP modeling of the SIMPLEX turbopump was performed in two phases. In the first phase of this investigation an initial, simplified model of SIMPLEX was developed based on an earlier model developed by Katherine Van Hooser. A detailed model that included all secondary flow passages was developed in the second phase.

Figure 3.1 depicts the circuit model of the SIMPLEX turbopump.

The heat addition due to the bearings is modeled using test data upstream of the first bearing and downstream of the second bearing. Test data of both pressure and temperature at these two positions allow for the calculation of the corresponding fluid enthalpies. The difference between these two enthalpies represent the heat added by the two bearings. The estimated heat source was equally distributed to nodes 110 and 112. In order to accurately measure the effect of the bearing heat addition on the axial thrust, heat was added to node 109 until the predicted temperature for this node matched the test data.

Rotation is modeled in branches 202, 205, 207, and 209. The k-factor (ratio of fluid rotational speed to the adjacent solid rotational speed) for branches 205 and 209 are still modeled using the smooth disc correlation developed earlier[3]. Nodes 202 and 207 are isolated and their k-factors are set such that the flowrate for branch 202 matches branch 203 and the flowrate for branch 207 matches branch 208.

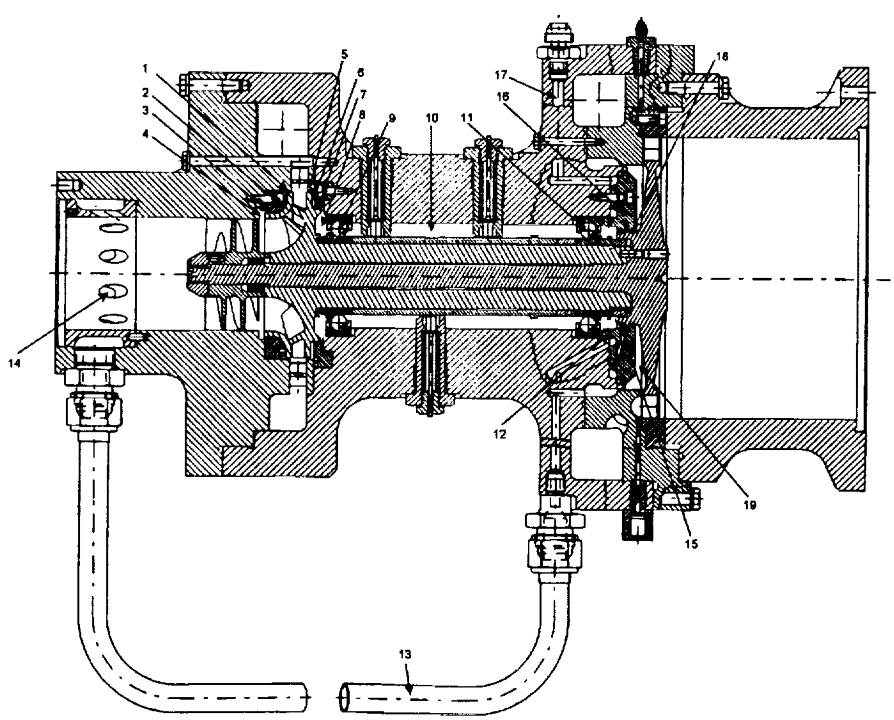

Figure 2.1: SIMPLEX Turbopump

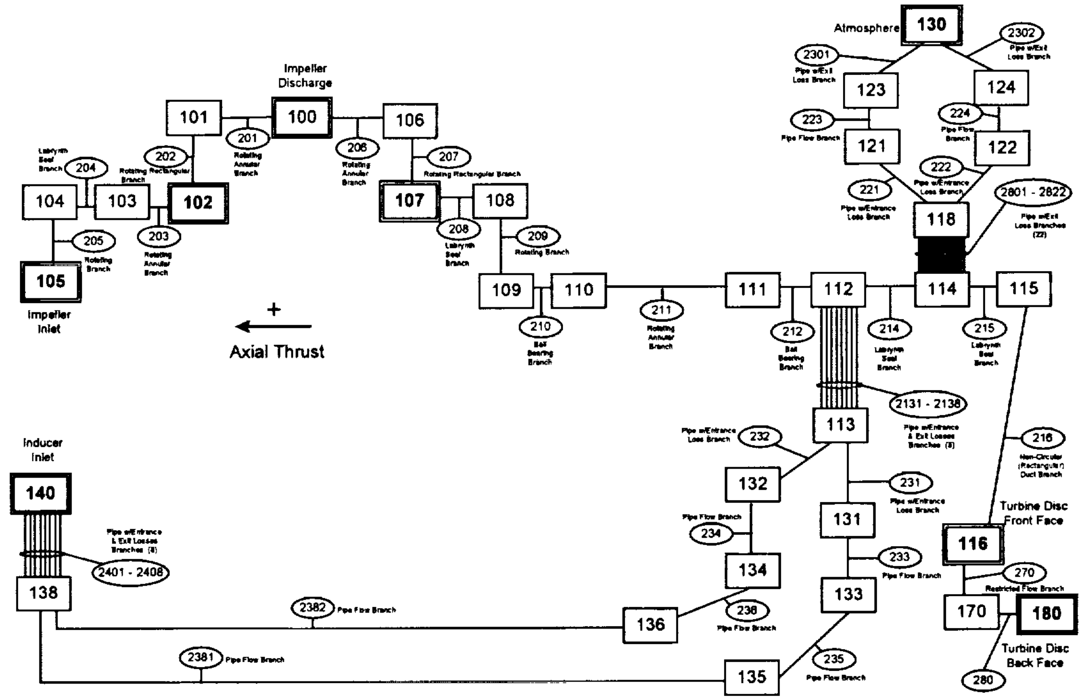

Figure 3.1: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model

4.0 RESULTS AND DISCUSSION

GFSSP SIMPLEX MODEL

The model was developed during the spring of 1997. The model used liquid oxygen tests (test # P2202L03 for 25,000 and 20,000 rpm, test # P2022L05 for 15,000 rpm) to obtain boundary conditions for nodes 102, 105, 107, 116, and 140. Nodes 102 and 107 are boundary nodes in the expanded model whereas these nodes were internal nodes in the initial model. Due to questionable test data associated with node 100, the boundary condition for node 100 was estimated. Nodes 130 and 180 were assumed to be at atmospheric conditions. Comparisons are presented for the following speeds: 25,000 rpm, 20,000 rpm and 15,000 rpm. A parametric study was performed on the k-factor for branch 209 for 25,000 rpm. Branch 209 was chosen due to its impact on the overall circuit (Branch 205 has a small change in radius - 1.688 inch outer radius, 1.50 inch inner radius. Branches 202 & 207 have minimal impact on the remainder of the model due to nodes 102 & 107 being boundary nodes in this model).

4.1 Modeling For Liquid Oxygen Operating at 25,000 rpm

Results of the modeling for the SIMPLEX turbopump using liquid oxygen operating at 25,000 rpm are presented in Figures 4.1, 4.2 and 4.3. The boundary conditions used for this model are presented in Table 4-1. The results show that the expanded model has excellent agreement to the test data (pressure nearly matched, temperature for 109 was forced to match, temperature for 112 matched using the enthalpy difference from the test data). The results show (Figure 4.3) that the flow rate through the bearings is 4.37 lbm/sec. Of this 4.37 lbm/sec, over half (2.52 lbm/sec) is returned to the inducer inlet and approximately one third is dumped overboard. Axial thrust for this case was calculated to be 565.3 lb_f towards the impeller (defined as a positive axial thrust).

Table 4-1: Expanded Model Boundary Conditions For Liquid Oxygen Operating at 25,000 rpm

Boundary Node Pressure

Boundary Node Temperature

p_{100} = 1100.0 psia (Assumed)	T_{100} = -286.6°F (Assumed)
p_{102} = 1078.0 psia	T_{102} = -286.6°F (Assumed)
p_{105} = 346.2 psia	T_{105} = -286.6°F
p_{107} = 1025.0 psia	T_{107} = -286.6°F (Assumed)
p_{116} = 62.6 psia	T_{116} = -265.6°F
p_{130} = 14.7 psia (Assumed)	T_{130} = -286.6°F (Assumed)
p_{140} = 93.7 psia	T_{140} = -286.6°F
p_{180} = 14.7 psia (Assumed)	T_{180} = -286.6°F (Assumed)

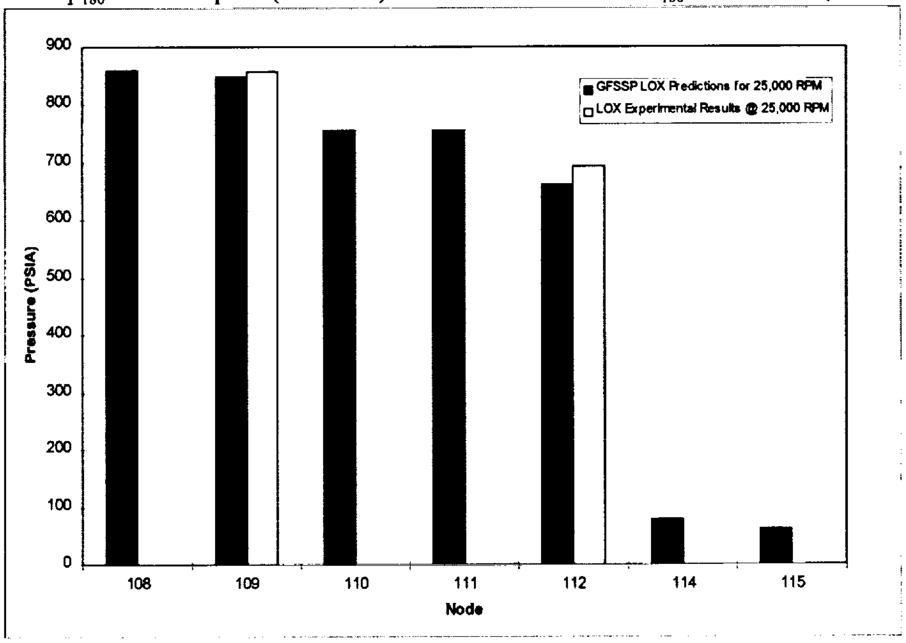

Figure 4.1: Internal Node Pressure Predictions for Liquid Oxygen Operating at 25,000 rpm - Expanded Model

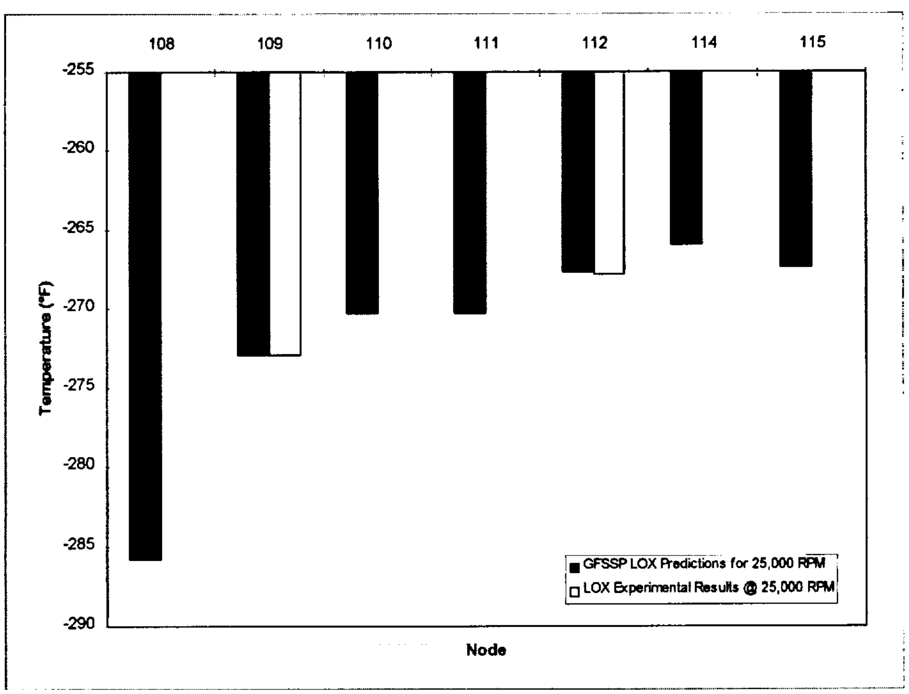

Figure 4.2: Internal Node Temperature Predictions for Liquid Oxygen Operating at 25,000 rpm - Expanded Model

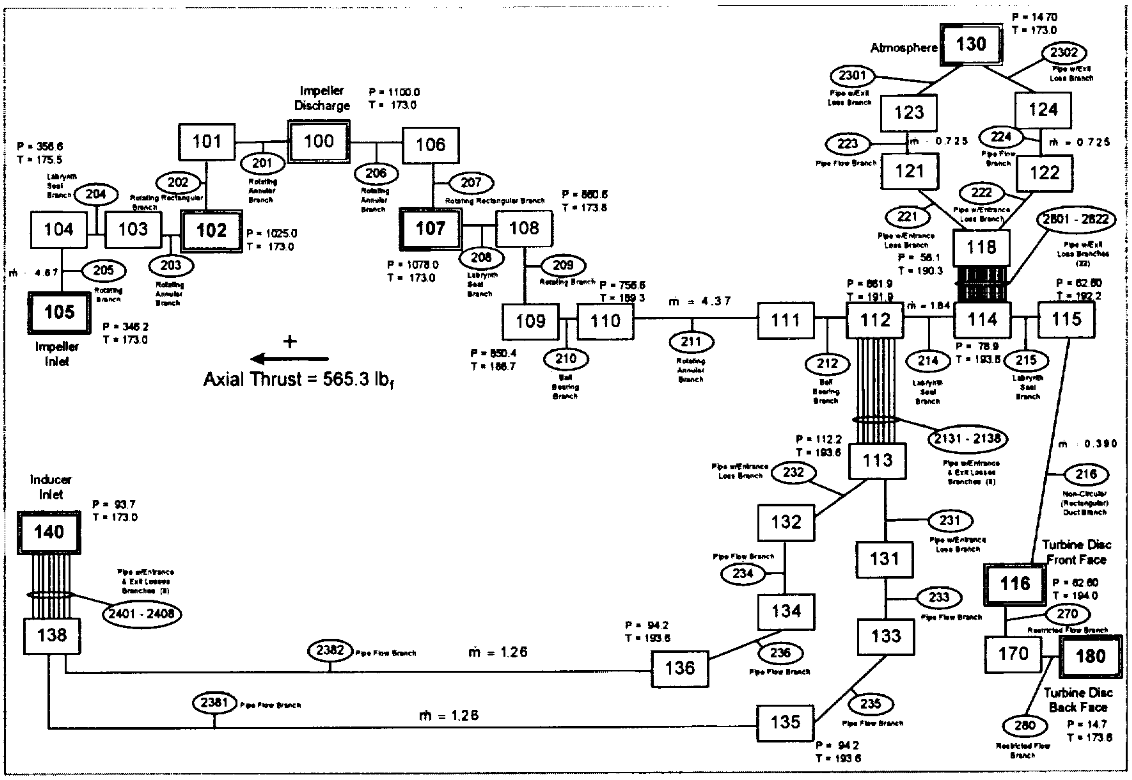

Figure 4.3: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model - Results for Liquid Oxygen Operating at 25,000 rpm

4.2 Parametric Study on the Effect of the K-Factor for Branch 209 - For Liquid Oxygen Operating at 25,000 rpm

Upon the successful demonstration of the model of the SIMPLEX turbopump operating at 25,000 rpm using liquid oxygen, a decision to perform a parametric study on the effect of the k-factor on the axial thrust. Due to the modifications incorporated into the model (changing nodes 102 and 107 from internal nodes to boundary nodes due to the questionable test data associated with node 100), branch 209 was chosen to be the only branch that would be used in the study. The study examined the variation of k_{209} from 0% to 500% of the nominal value used in the baseline expanded model ($k_{209\ \text{baseline expanded model}} = 0.1122$). Figure 4.4 displays the result of the study for $k_{209} = 0.0$ (corresponding to 0%). Note that the axial thrust increased by ~3%. This small increase is due to the low baseline value of k_{209}. Figure 4.5 shows the result of the study for $k_{209} = 0.561$ (corresponding to 500%). For this case the axial thrust dropped by ~55%. Figure 4.6 summarizes the variation of axial thrust caused by the variation of k_{209}. As is seen in Figure 4.6, axial thrust shows a strong dependence on k_{209}.

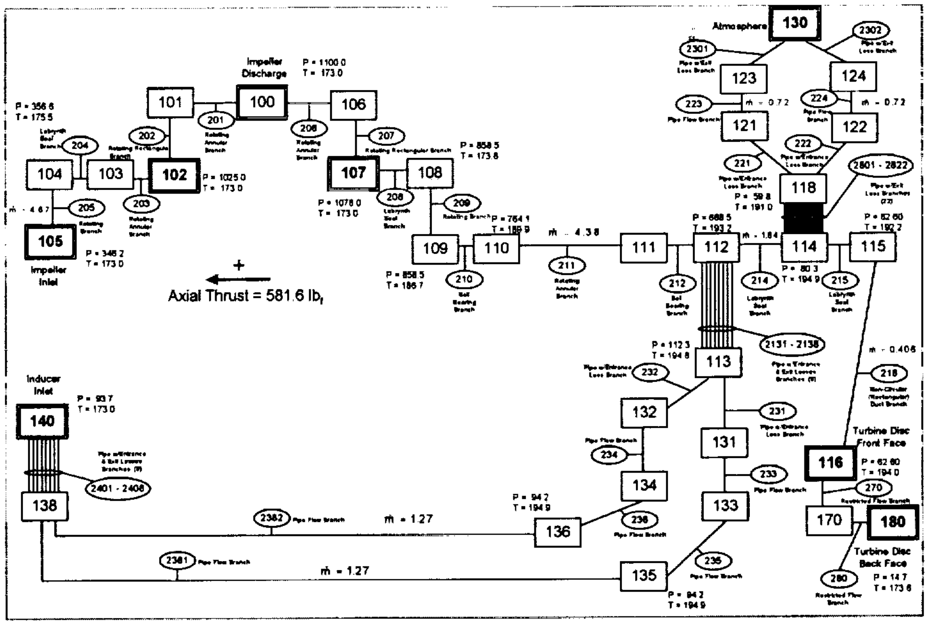

Figure 4.4: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model - Parametric Study Results for k_{209} = 0.0 (Liquid Oxygen Operating at 25,000 rpm)

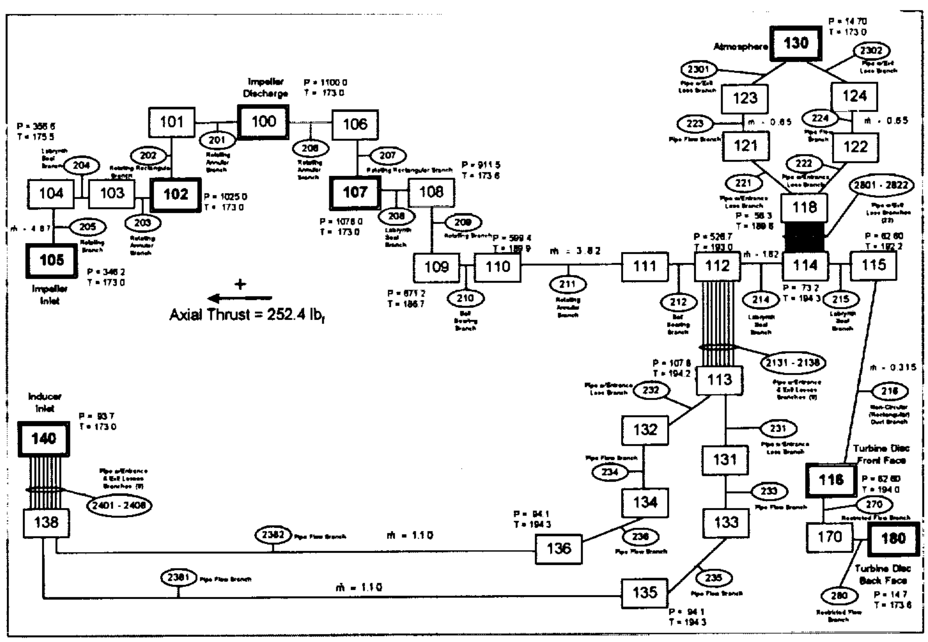

Figure 4.5: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model - Parametric Study Results for k_{209} = 0.561 (Liquid Oxygen Operating at 25,000 rpm)

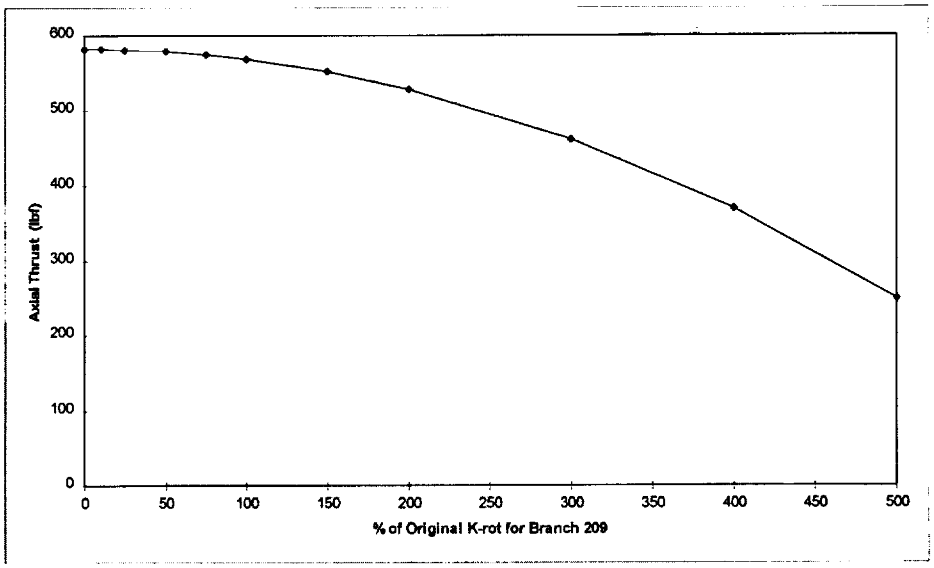

Figure 4.6: Parametric Study Axial Thrust vs. k_{209} Results Summary (Liquid Oxygen Operating at 25,000 rpm)

4.3 Modeling For Liquid Oxygen Operating at 20,000 rpm

Results of the modeling for the SIMPLEX turbopump using liquid oxygen operating at 20,000 rpm are presented in Figures 4.7, 4.8 and 4.9. The boundary conditions used for this model are presented in Table 4-2. The results again show that the model has excellent agreement to the test data. The results show (Figure 4.9) that the flow rate through the bearings is 3.52 lbm/sec. Of this 3.52 lbm/sec, over half (1.97 lbm/sec) is returned to the inducer inlet and almost one third is dumped overboard. Axial thrust for this case was calculated to be 283.3 lb_f towards the impeller (a ~50% reduction from the 25,000 rpm case).

Table 4-2: Expanded Model Boundary Conditions For Liquid Oxygen Operating at 20,000 rpm

Boundary Node Pressure	Boundary Node Temperature
p_{100} = 750.0 psia (Assumed)	T_{100} = -277.6°F (Assumed)
p_{102} = 684.9 psia	T_{102} = -277.6°F (Assumed)
p_{105} = 286.0 psia	T_{105} = -287.1°F
p_{107} = 738.1 psia	T_{107} = -277.7°F (Assumed)
p_{116} = 38.5 psia	T_{116} = -275.5°F
p_{130} = 14.7 psia (Assumed)	T_{130} = -286.6°F (Assumed)
p_{140} = 121.1 psia	T_{140} = -287.1°F
p_{180} = 14.7 psia (Assumed)	T_{180} = -286.0°F (Assumed)

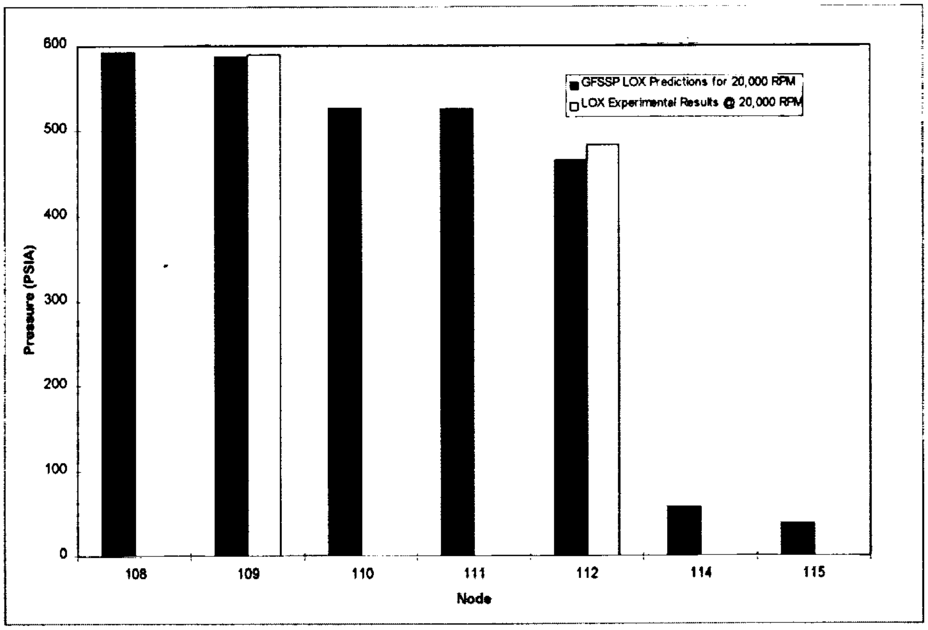

Figure 4.7: Internal Node Pressure Predictions for Liquid Oxygen Operating at 20,000 rpm - Expanded Model

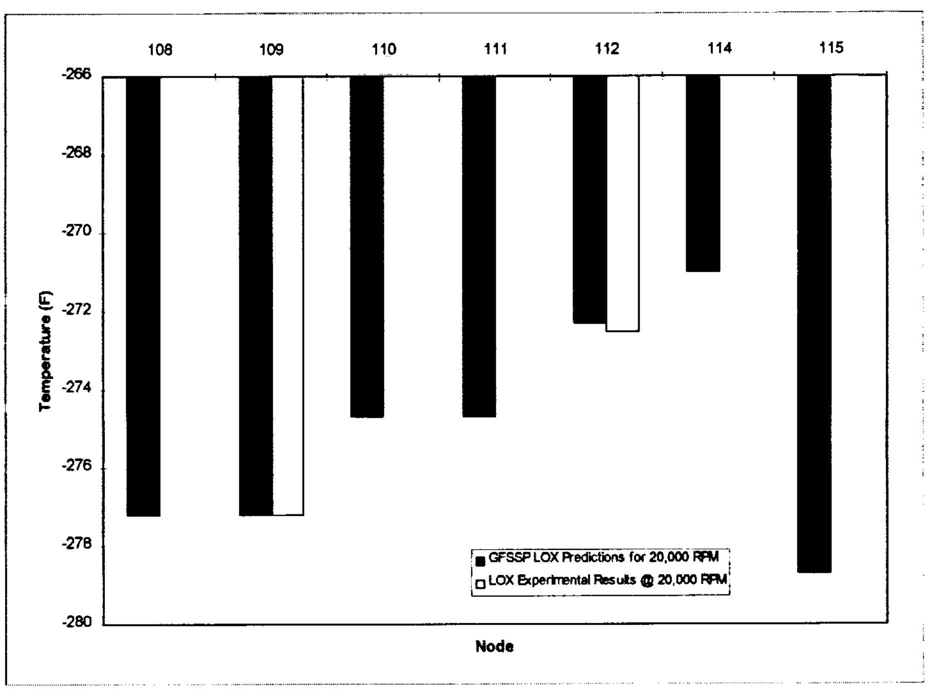

Figure 4.8: Internal Node Temperature Predictions for Liquid Oxygen Operating at 20,000 rpm - Expanded Model

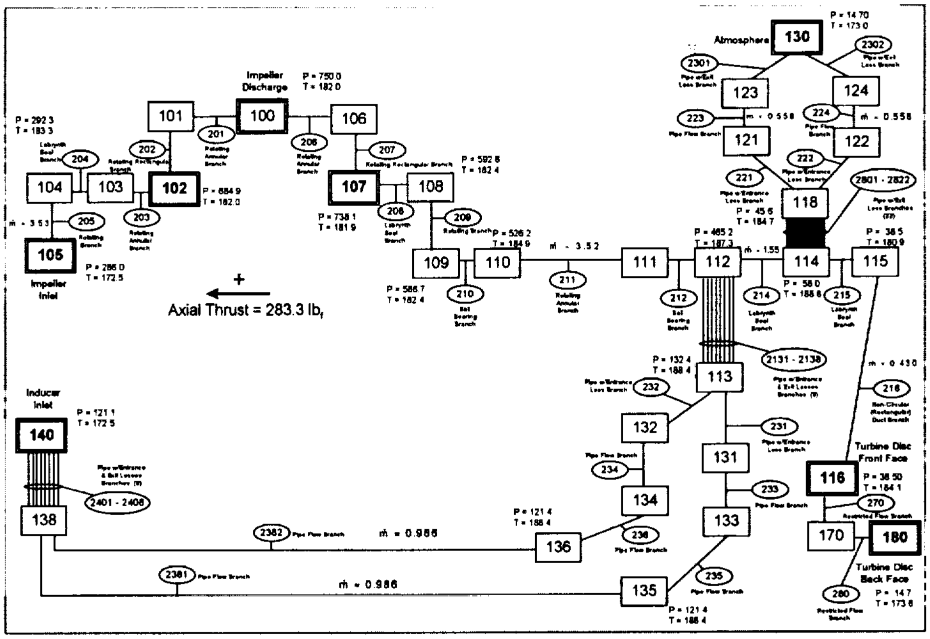

Figure 4.9: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model - Results for Liquid Oxygen Operating at 20,000 rpm

4.4 Modeling For Liquid Oxygen Operating at 15,000 rpm

Results of the modeling for the SIMPLEX turbopump using liquid oxygen operating at 15,000 rpm are presented in Figures 4.10, 4.11 and 4.12. The experimental data used for this model came from a different test than that used in the 20,000 rpm and 25,000 rpm models. The boundary conditions used for this model are presented in Table 4-3. The results again show that the expanded model has excellent agreement to the test data. The results show (Figure 4.12) that the flow rate through the bearings is 2.95 lbm/sec. As in the 25,000 rpm and 20,000 rpm cases, over half of the bearing coolant flow (1.62 lbm/sec) is returned to the inducer inlet and almost one third is dumped overboard. Axial thrust for this case was calculated to be 179.9 lb$_f$ towards the impeller (a ~36% reduction from the 20,000 rpm case).

Table 4-3: Expanded Model Boundary Conditions For Liquid Oxygen Operating at 15,000 rpm

Boundary Node Pressure	Boundary Node Temperature
p_{100} = 555.0 psia (Assumed)	T_{100} = -287.1°F (Assumed)
p_{102} = 512.7 psia	T_{102} = -287.1°F (Assumed)
p_{105} = 243.7 psia	T_{105} = -287.1°F
p_{107} = 534.7 psia	T_{107} = -287.1°F (Assumed)
p_{116} = 24.7 psia	T_{116} = -284.2°F
p_{130} = 14.7 psia (Assumed)	T_{130} = -286.6°F (Assumed)
p_{140} = 114.7 psia	T_{140} = -287.1°F
p_{180} = 14.7 psia (Assumed)	T_{180} = -286.0°F (Assumed)

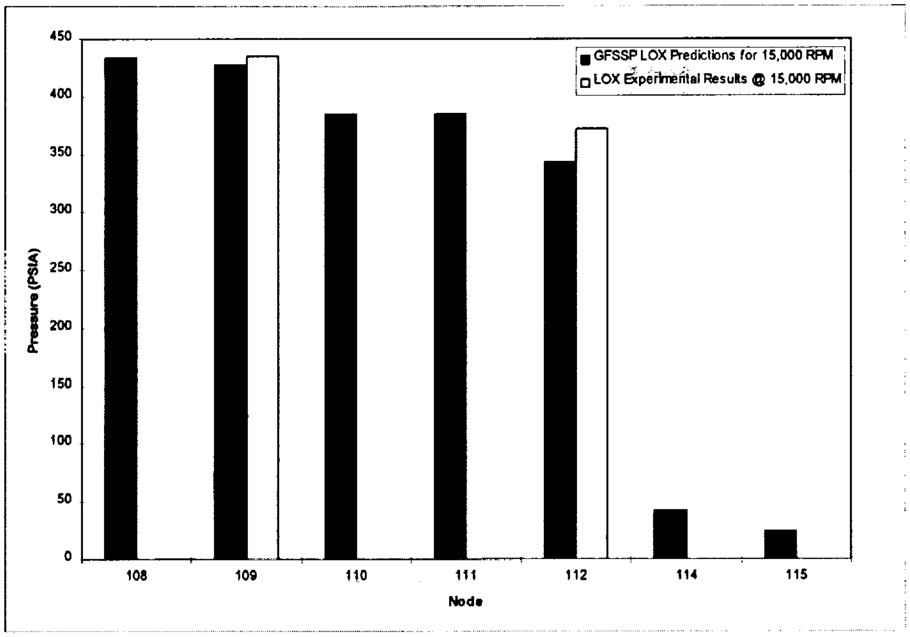

Figure 4.10: Internal Node Pressure Predictions for Liquid Oxygen Operating at 15,000 rpm - Expanded Model

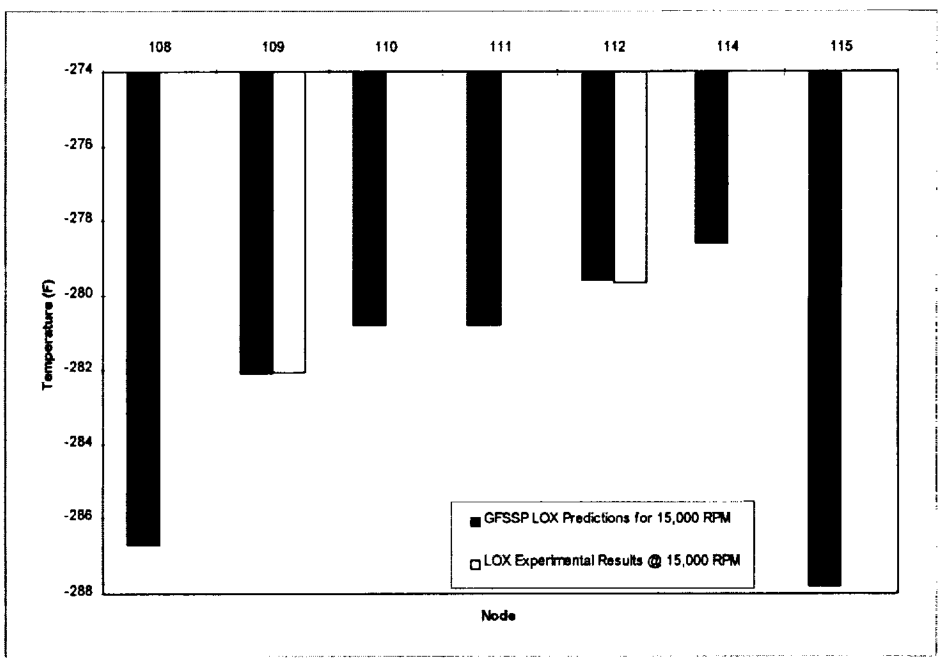

Figure 4.11: Internal Node Temperature Predictions for Liquid Oxygen Operating at 15,000 rpm - Expanded Model

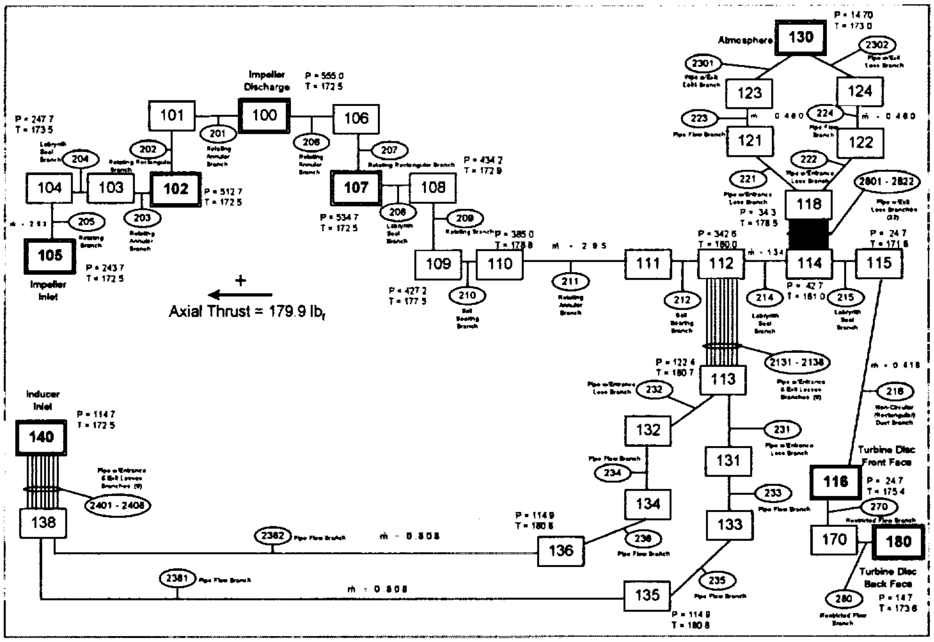

Figure 4.12: Expanded GFSSP SIMPLEX Turbopump Secondary Flow Model - Results for Liquid Oxygen Operating at 15,000 rpm

5.0 SUMMARY

This paper describes the modeling of the secondary flow circuit and axial thrust calculation for the SIMPLEX turbopump utilizing one-dimensional fluid flow code (GFSSP). The model encompasses all of the secondary flow paths within the SIMPLEX turbopump. Additionally, the model calculates the axial thrust based on the calculated pressures and user defined areas for particular nodes.

Results from the model showed very good agreement with the test data (pressure and temperature) for the three liquid oxygen models developed. The results show the axial thrust increases dramatically with the running speed of the turbopump. A parametric study was performed on the k-factor for branch 209. This study showed the importance of the k-factor on the axial thrust.

6.0 RECOMMENDATIONS

It is recommended that a new resistance option be added into GFSSP for the modeling of the bearings. This option would account not only for the flow resistance from the bearings, but also would account for the heat addition to the fluid due to the bearings.

Based on the parametric study on the k-factor for branch 209, it is also recommended that more recent experimental data be provided to develop additional k-factor correlations utilizing the method described in reference 6.

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