Siemens Digital Industries Software

Aircraft fuel system simulation in Simcenter Flomaster: 3D CFD characterization

Executive summary

This final paper in the aircraft fuel system series will address a common issue with 1D system models. That is, how to add the required detail to the model for complex components that cannot easily be represented through correlations or empirical data. These types of components can be common in aircraft systems.

To get the data for these types of components engineers have two options; physical testing and 3D CFD. Physical testing can be extremely costly and is difficult to get data for all possible operational scenarios. 3D CFD can be very time consuming and usually requires an expert user to get results that are reliable.

This paper will go into detail on how 3D CFD (Simcenter FLOEFD™ software) used in conjunction with Simcenter Flomaster™ software can quickly and accurately characterize complex components without the need for a CFD analyst and provide an added level of robustness to an aircraft fuel system model.

Mike Croegaert

Introduction

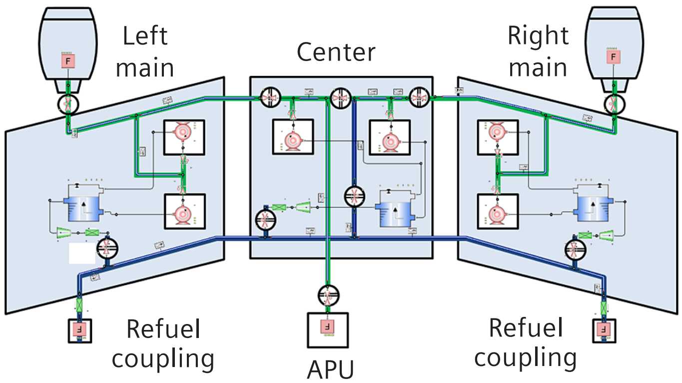


Figure 1: Basic fuel system schematic.

The basic fuel system: a review

Before going into the details of utilizing 3D CFD to characterize complex components in a fuel system model, it is appropriate to review the fuel system model as it was created in the previous white papers.

Figure 1 is the schematic representation of the simplified passenger aircraft fuel system that was built and used in the previous white papers in this series. The three large blue sections represent the wing and the center fuel tanks, the white boxes represent pumps, and the fuel feed and transfer plumbing is represented in green, and refueling lines are represented in dark blue. Shut off valves are depicted throughout the model as the circular symbols, indicating normally open or normally closed. The Simcenter Flomaster system model is drawn directly on top of the schematic image. It includes source components for our boundary conditions, and extra loss components for items like filters and couplings. Again, the tanks do not take up the whole area outlined in light blue, but instead are single discrete components. The thin link lines represent a direct connection between adjacent components, but they are not pipes themselves. Nodes sit in the middle of the links and serve as convenient points to enter elevation data and interrogate flow results of temperature and total pressure. In the previous papers a more detailed examination of the arrangement of the pipes, pumps, valves and tanks was conducted. For a more thorough explanation of the base model, you can refer to the papers:

Aircraft fuel system simulation in Simcenter Flomaster: Basic simulation

Aircraft fuel system simulation in Simcenter Flomaster: Adding active control

Aircraft fuel system simulation in Simcenter Flomaster: Advanced wing tank modeling with venting and inerting

This study, will focus specifically on the wing tank system in detail.

Solving pump limitations

In this model, the fuel is drawn from the tanks with mechanical fuel pumps. This works quite well, but as the model is refined, and there is a need to take other design considerations into account, the model might run into some limitations on where the pumps can be placed. Furthermore, most mechanical pumps must be fully wetted to function properly. This means that sometimes, there is unusable fuel left in the bottom of the tank.

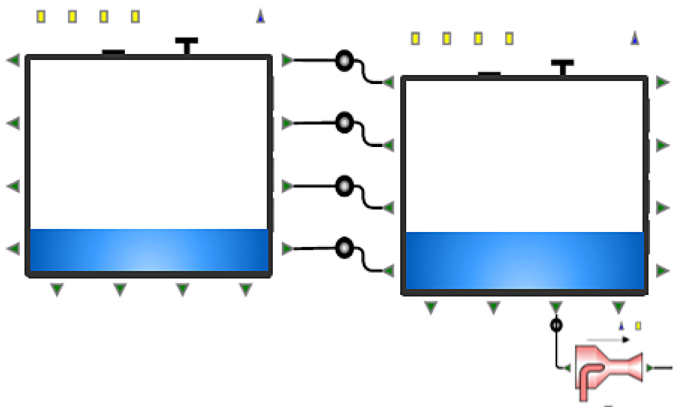


Figure 2: Basic fuel tank configuration.

One solution is to add jet pumps that can be placed in the lowest portion of the tank. These pumps have no moving parts and can scavenge the last remaining amount of fuel. Additionally, a constant issue for any aircraft is water condensation within the tank. Any water in the fuel will tend to settle to the bottom of the tank because of density differences. An additional benefit to our added jet pump is that any small amount of water that accumulates can be removed before a large build up could cause harm.

Figure 3 shows the updated fuel system model from the previous paper with the addition of a jet pump and collector cell to each set of wing tanks.

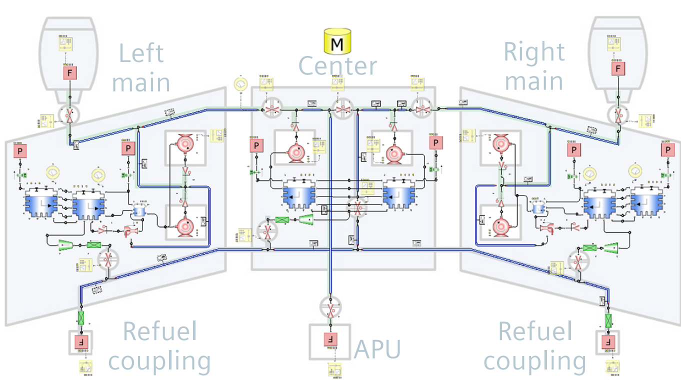


Figure 3: Detailed fuel system model with jet pumps.

Now examining the left hand wing tank. It can be seen that the inner wing tank is now connected to a smaller collector cell. Instead of drawing from the inner tank, the mechanical fuel pumps now pull fuel from this cell. There is a gravity feed connection between the inner tank and the collector cell, but due to structural constraints, this connection does not extend to the very bottom of the inner tank. Left unaided, this amount of fuel would go unused.

To extract the fuel from the inner wing tank once it gets too low to gravity feed, we've added a jet pump with the suction side connected to the lowest sump point on the inner wing tank. The pump feeds the collector cell by using the motive energy provided by a small amount of high pressure fuel bled directly from the mechanical fuel pumps.

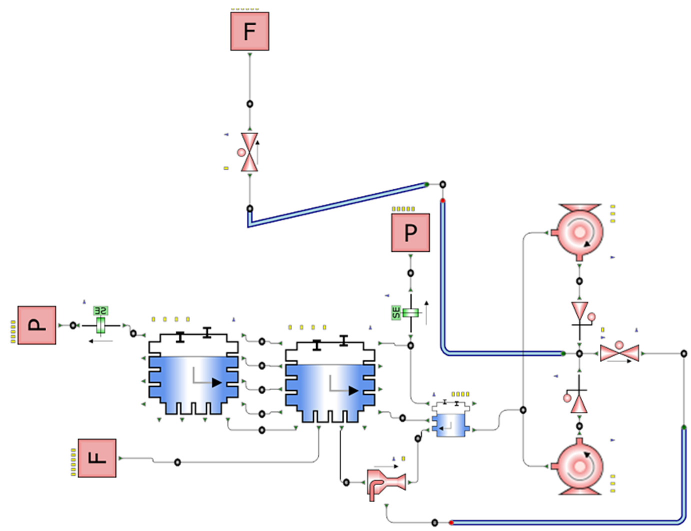


Figure 4: Wing tank model detail.

Jet pump modeling requirements

In contrast to most other components in Simcenter Flomaster, the jet pump does not come pre-supplied with performance data. Instead, the user has two options to define performance. The first method is to enter detailed geometry for the pump and Simcenter Flomaster can apply a built in empirical correlation for jet pump behavior.

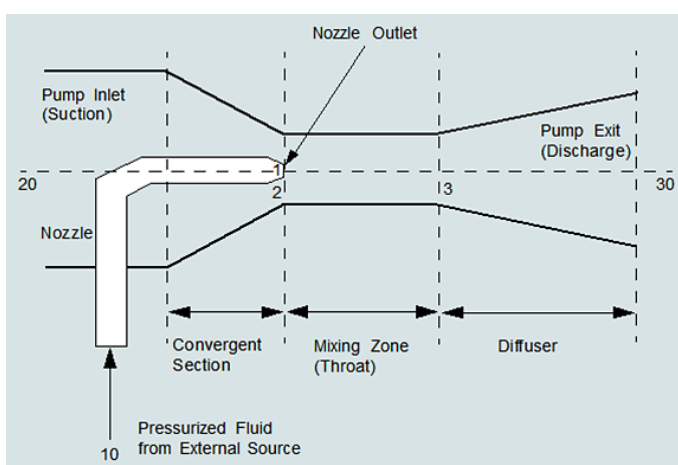


Figure 5: Typical jet pump.

The second option is a more rigorous data based approach. The pump requires a curve of flow ratio vs head ratio and a curve of motive flow rate vs pressure difference between the motive and suction arms. This data can come from many sources, including the vendor of the pump, physical testing, or what will be discussed in this paper, 3D computational fluid dynamics.

3D-1D characterization using Simcenter FLOEFD

Simcenter Flomaster has a sister 3D CFD software – Simcenter FLOEFD, and the two tools have a unique communication interface that allows data to be easily passed from Simcenter FLOEFD into Simcenter Flomaster as complete characterized models in the form of response surfaces.

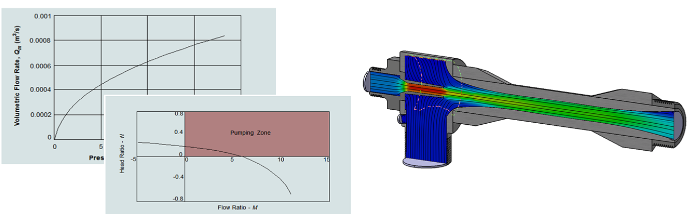


Figure 6: Jet pump characteristic data.

Simcenter FLOEFD has several key technologies that make it a very good fit for 1D data generation for Simcenter Flomaster.

Simcenter FLOEFD is CAD embedded, it runs inside of several CAD packages including CATIA V5, PTC Creo, Siemens NX and as a standalone tool using the Solidworks engine. For this paper, the CATIA version is used since it is prevalent throughout the aerospace industry.

Simcenter FLOEFD is designed as a tool for engineers as well as seasoned CFD analysts, it applies automated modified wall functions to properly capture boundary layer effects regardless of the density of the mesh in the boundary layer. It also has an automated solver to determine the flow regime between laminar, turbulent or transitional without user intervention. Most importantly, Simcenter FLOEFD has a unique and automated mesher. The mesher is geometry aware. If the CAD geometry changes, the mesh changes automatically. It's also optionally solution adaptive, updating as the problem solves, intelligently putting more mesh where it's needed. Since Simcenter FLOEFD is completely CAD embedded, the user can run parametric studies, not only varying flow conditions, but also the actual geometry over the course of a study. The parametric tool has a built-in Simcenter Flomaster export utility that makes getting data back to Simcenter Flomaster as seamless as possible.

In CATIA, Simcenter FLOEFD shows up as its own workbench and adds some elements to the project tree. To start a new project from bare CAD, the user simply runs the project wizard from the Simcenter FLOEFD menu.

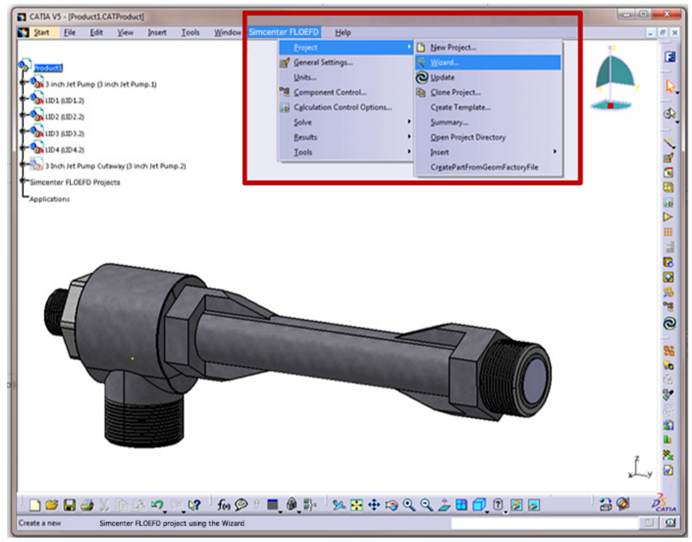


Figure 7: Jet pump model in CATIA V5.

Simcenter FLOEFD's engineering user interface allows the user to set up a project in a step-by-step fashion. This includes choosing units; the physics to consider in the simulation including heat transfer, gravity effects and rotation; the fluids to use in the simulation, and lastly; the initial conditions like temperature, pressure and initial velocity.

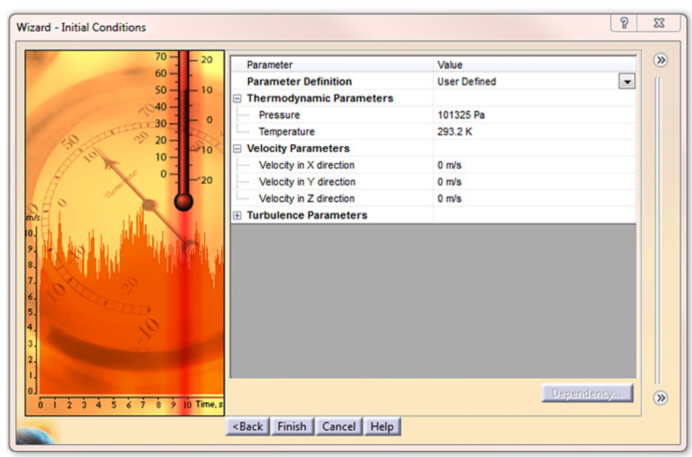


Figure 8: Simcenter FLOEFD project wizard.

Once the wizard is complete, the geometry can be prepared for simulation. For an internal flow problem such as the jet pump, all the openings need to be fully sealed. Simcenter FLOEFD has an automated tool that can generate what are called 'lids' on any hole or gap. Once the geometry is sealed, Simcenter FLOEFD performs a check and builds a solid model of the internal fluid cavity.

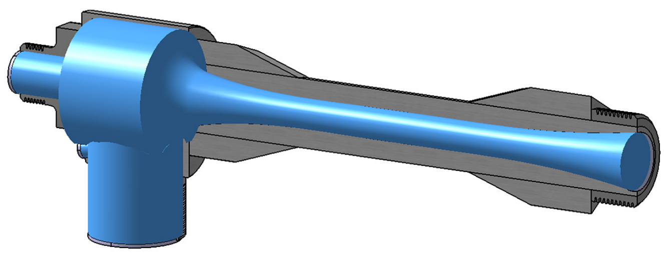


Figure 9: Simcenter FLOEFD computational domain.

Simcenter FLOEFD then calculates a computational domain surrounding the relevant fluid geometry. The user could resize this or even slice the volume in half and do an axisymmetric simulation to save computational resources. Then the boundary conditions must be manually applied to any face in the model, although typically the lids are the boundary conditions. Simply click a face and add a new boundary. The engineer can combine multiple faces, switch between flow, pressure and wall boundary types and even add swirl or a non-uniform velocity profile by transferring results from a different study.

The mesh, although highly automated, can be manually driven to add grid cells where they are needed. The first step is with a simple slider bar that spans from one to seven. This controls the number of refinement steps the mesh will take as needed, with each step creating eight grid cells in place of its lower level parent cell. At higher

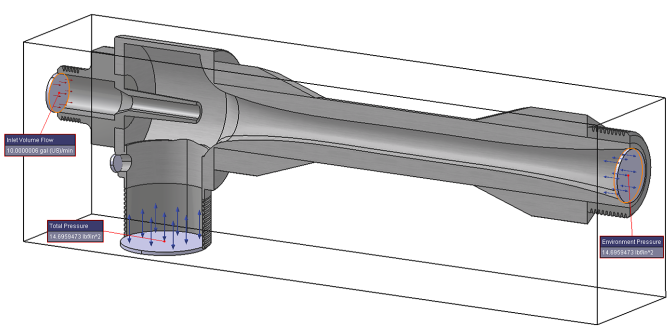


Figure 10: Applying boundary conditions in Simcenter FLOEFD.

levels, advanced features like solution adaptive refinement are automatically invoked. Simply specify minimum gaps that you want properly resolved, and you can automatically ignore thin gaps, something very commonly found in large CAD assemblies.

The mesh can be manually refined as well by selecting specific geometry, adding optional control planes or even disabled bodies into the CAD model to serve as mesh structure.

Once the model is prepared, boundary conditions are set and goals determined, the simulation is run via the run command. Running the simulation launches the solver. The solver is the only aspect of Simcenter FLOEFD that does not happen directly in CAD, instead, a second window is launched to monitor the progress of the solution. Custom defined preview plots for parameters like pressure, velocity and even the mesh can be created. Goals can also be plotted to have a real time monitor on their current value and their trend toward convergence. The solver can run locally or on a remote Windows or Linux machine. Parametric studies can be performed on multiple machines at once to improve performance.

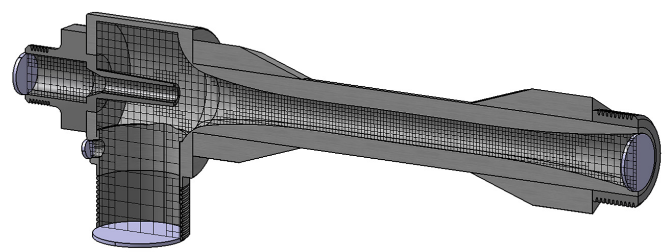


Figure 11: Simcenter FLOEFD adaptive mesh.

Once the solve is complete, the results are loaded back into the CAD interface. Here you can draw results directly on the native CAD. The first example of a result

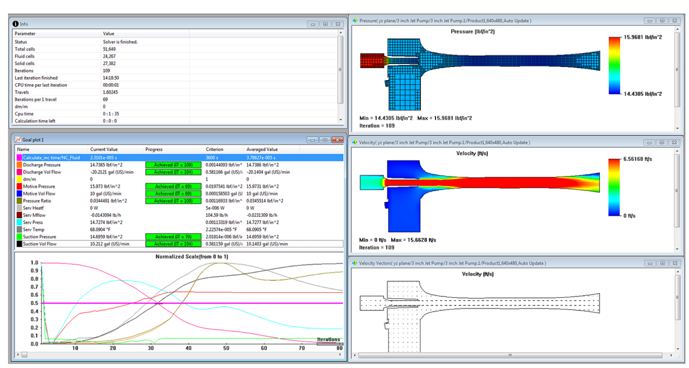
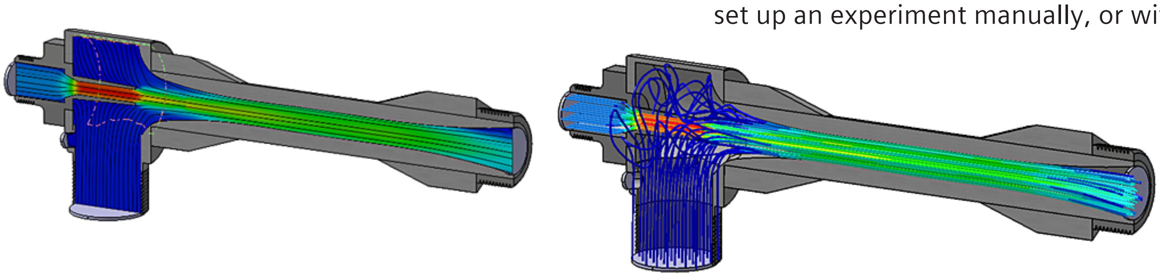


Figure 12: Solution monitor in Simcenter FLOEFD.

is a cut plot. This one shows contours of velocity with overlaid streamlines. The cut plane can be manually adjusted with a live preview. Simcenter FLOEFD can also generate three dimensional flow trajectories inside of the fluid region. Additionally, tabular results like goals can be drawn or exported to other tools like Microsoft Excel.

For Simcenter Flomaster component characterization, multiple simulations need to be run to generate data over a wide range of flow conditions. To do that the parametric study tool built into Simcenter FLOEFD is utilized. This tool leverages the parametric capabilities of the 3D CAD packages that Simcenter FLOEFD integrates with, to allow the user to vary boundary conditions, dimensions or constraints in the model. To use it, simply set up an experiment manually, or with an automated



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Motive Vol Flow	[gal (US)/min]	10.0000	10.0000	10.0000	10.0000	100	Yes	6.1250e-010	0.0002
Suction Vol Flow	[gal (US)/min]	10.2120	10.1403	9.9333	10.2235	100	Yes	0.2902	0.5812
Discharge Vol Flow	[gal (US)/min]	-20.2121	-20.1404	-20.2235	-19.9335	100	Yes	0.2900	0.5812
Pressure Ratio	[lbf/in^2]	0.03	0.03	0.03	0.03	100	Yes	1.13e-003	1.17e-003

Figure 13: Sample results from Simcenter FLOEFD.

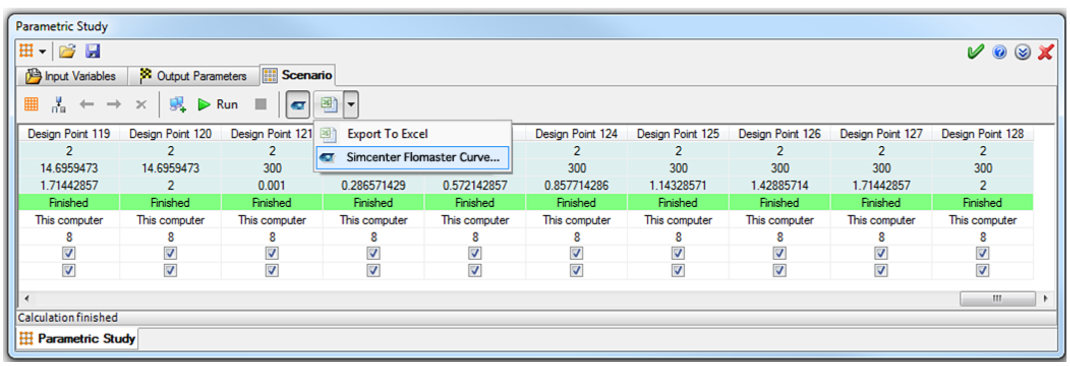

Figure 14: Simcenter FLOEFD parametric study wizard.

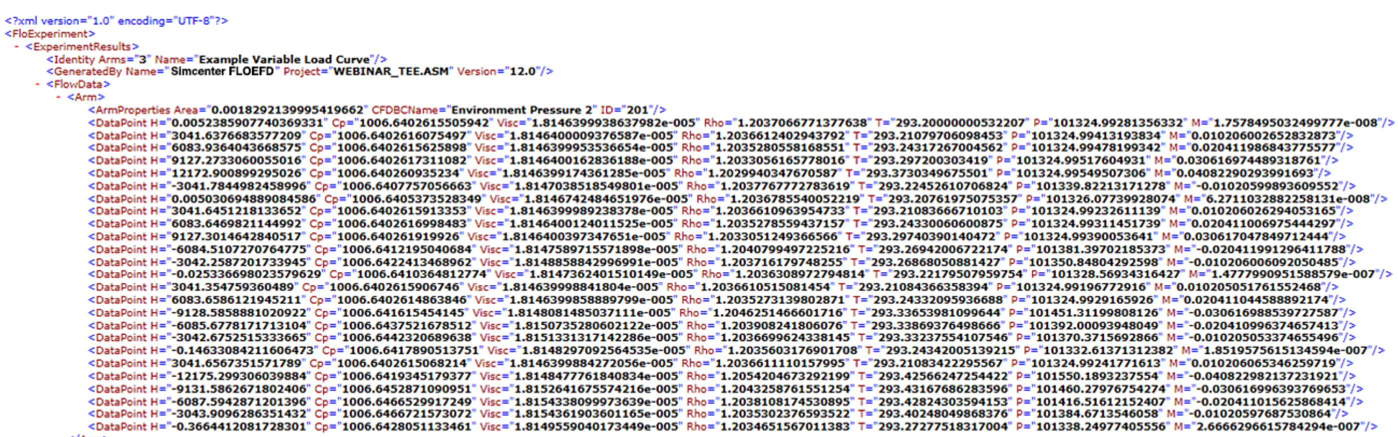

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Figure 15: Raw data from parametric study.

range of values. Select the goals that need to be solved for, though everything that Simcenter Flomaster needs to build a component will automatically be extracted. Once the study is complete, select the Simcenter Flomaster curve export option and save it to a file.

That file is a raw record of the flow conditions at each boundary at each experiment point. Each point contains data for flow rate, pressure, temperature, density, viscosity, enthalpy and heat capacity. From this data, nondimensionalized curves can be created so that Simcenter Flomaster can extrapolate performance of the part over a wide range of fluids, temperature, and pressures.

Once the Simcenter Flomaster curve is created, it can be imported into Simcenter Flomaster either as an individual data curve or as a complete component. To do this, right click on the component catalog and create a new 'Simcenter FLOEFD component'. Simcenter Flomaster will parse the data and automatically determine what type of component to create.

The component creation tool will preview the parsed and calculated performance data. The first curve a jet pump needs, Flow ratio vs Head ratio and the other mandatory curve, Motive flow rate vs Pressure difference. Once this step is done, Simcenter Flomaster adds the component to the catalog and automatically populates it with the data just generated.

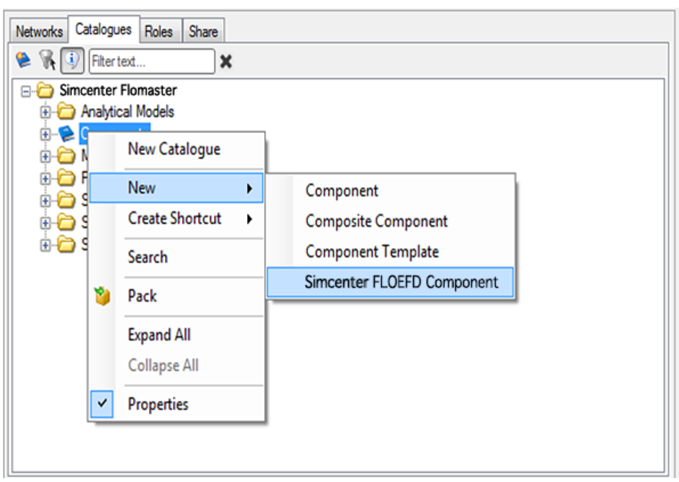

Figure 16: Importing data into Simcenter Flomaster.

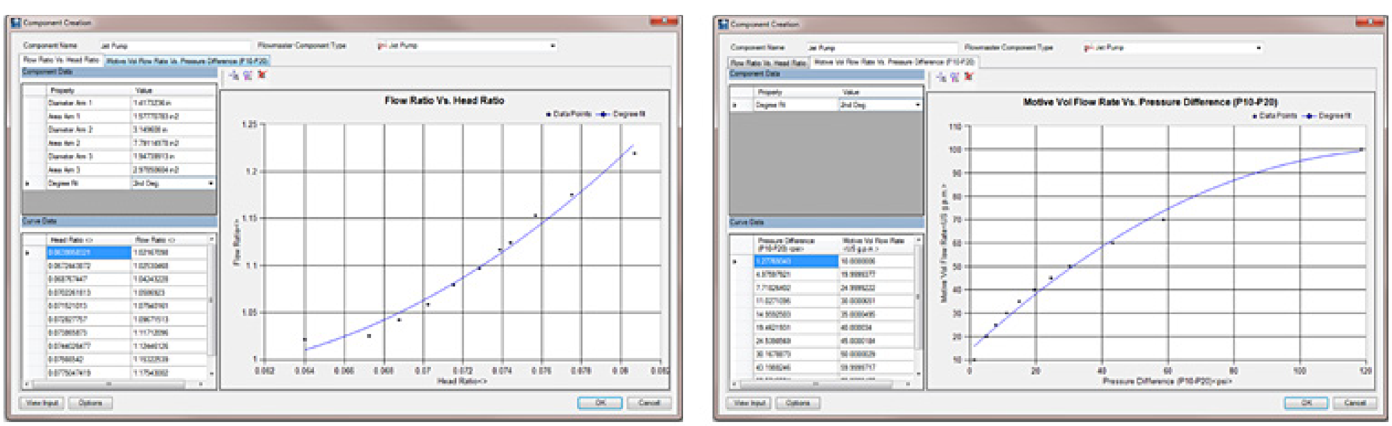

Figure 17: Jet pump characteristic curves in Simcenter Flomaster.

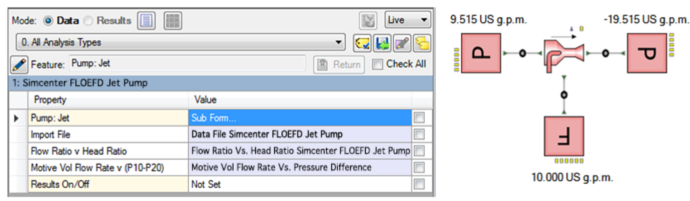

Figure 18: Jet pump unit test.

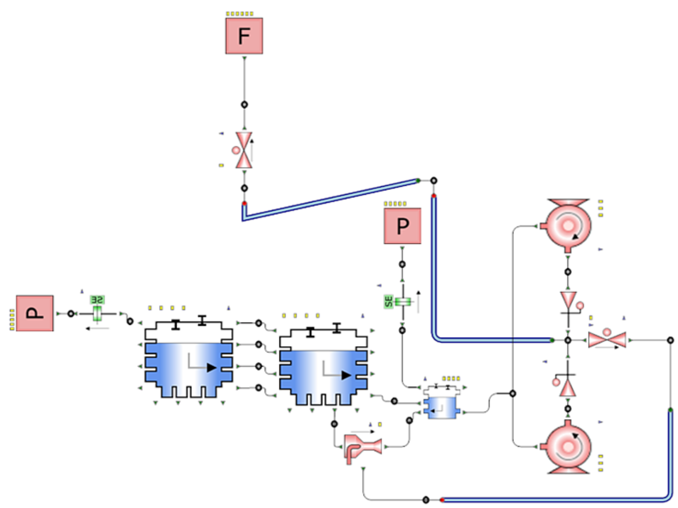

Figure 19: Adding characterized jet pump to system model.

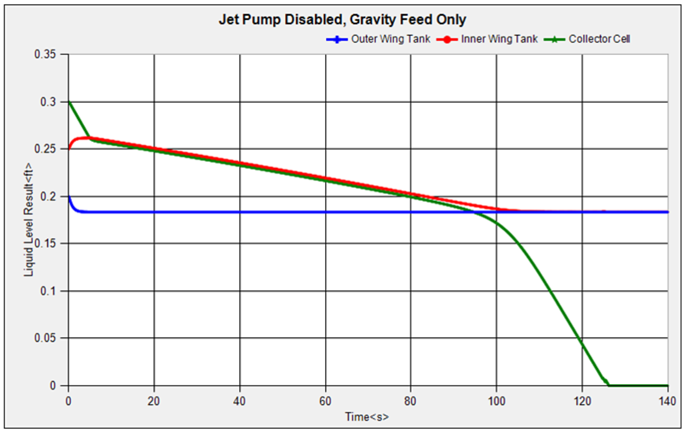

Figure 20: Scenario 1 – Jet pump inactive.

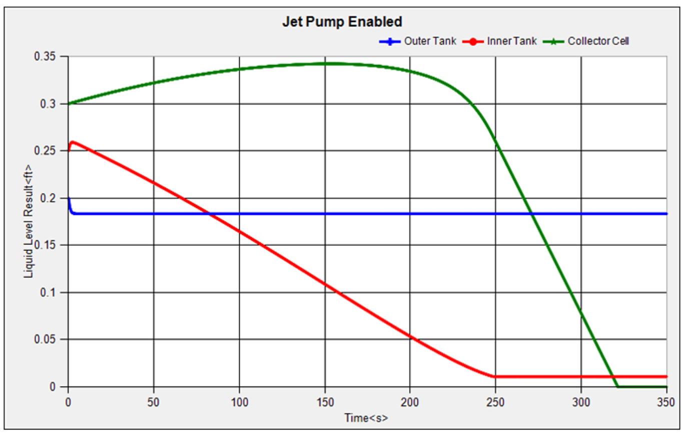

Figure 21: Scenario 2 – Jet pump active.

Before using the component in the fuel system model it will first be verified in a unit test. Unlike most components, Simcenter FLOEFD sourced components require no further data to use, relevant data like the curves are pre-applied. All that is required to run a unit test is to add boundary conditions and run an analysis and the component should perform exactly as Simcenter FLOEFD predicted during the characterization step.

After the unit test has verified the component was created correctly, the jet pump can be added to the fuel system model and run a series of analyses.

Two transient simulation scenarios will be examined. In the first simulation, the jet pump has been included but blocked the motive flow, so the tanks will only feed into the collector cell via gravity. The connection between each section of the tanks is via a series of holes in the ribs that separate each compartment. These holes span almost the entire height of the tank, but the bottom two inches of the tank is blocked by structure.

As shown with the blue line, the outer tank is draining briefly into the inner tank marked in red. The outer tank stops flowing as the level of fuel drops below the holes in the rib. Rendering the remaining two inches of fuel in that tank unusable. The inner tank in red and the collector cell in green both drain together. The collector cell is drained via the mechanical fuel pumps and the inner tank drains via gravity into the cell until it too reaches about two inches of height and can no longer drain. The tank is exhausted of all usable fuel in about 125 seconds.

The second case has the jet pump enabled. Here, the jet pump is moving fuel from the inner tank to the collector cell at a rate of about ten gallons per minute. In this case, the inner tank drains much faster, but that fuel is being transferred to the collector cell to feed the pumps. Because the suction inlet to the jet pump can be placed at the lowest point in the tank, it can drain almost all of the fuel out of it before it stops providing flow. At this point, the fuel level in the collector cell starts to drop quickly until it is completely exhausted. In this case, because more fuel is available, the tank does not drain for 320 seconds, a significant improvement.

Conclusion

This paper examined the problem of unusable fuel and how adding specialty pumps like jet pumps to the design can help with fuel scavenging. It discussed how the jet pump has unique performance data requirements that make them a good candidate for characterization via CFD. To do that, the paper showed how this can be done with Simcenter FLOEFD, a fast and easy to use CAD embedded 3D CFD Tool. A parametric study was performed on a sample jet pump, automatically exported the data to Simcenter Flomaster and then included it in the 1D Analysis. This was done to show how using complimentary tools can add robustness to the system simulation.

This is the last paper in this series, so to recap what has been covered.

Aircraft fuel system simulation in Simcenter Flomaster: Basic simulation presented the modeling of a typical aerospace fuel system, and introduced the model and performed a few basic but important initial flow studies. These studies solved real world issues such as identifying an optimum pipe size for the refueling line, and selecting flow restrictors to balance flow. It was able to determine the system pressure required to reach our desired design flow rate. Finally it examined a transient analysis scenario to understand the effect of valve closure timing on pressure wave propagation.

Aircraft fuel system simulation in Simcenter Flomaster: Adding active control presented the modeling of a typical aerospace fuel system, and it was shown how active controls, including a pre-scripted flight profile can be applied to the model to simulate a complete flight and help achieve the goal of maximum fuel storage in the wing tanks while avoiding complicated piping, or opening the design up to single points of failure such as single isolation valves. The periodic resupply is designed to strike a balance between continuous pumping and a constant fuel level in the wings. This has demonstrated that adding controls can add significantly more capability to fuel system models and enables users to simulate and analyze both simple situations and very complex control behavior.

Aircraft fuel system simulation in Simcenter Flomaster: Advanced wing tank modeling with venting and inerting presented the modeling of a typical aerospace fuel system, examined how advanced tanks can bring new capability to the fuel and vent system models by allowing the user to combine the liquid fuel circuit with the compressible gas circuit in a single model. The addition of a complete venting system to a fuel system model adds a general level of fidelity but also provides the ability to look at new scenarios. Important issues like tank venting under conditions of stress such as rapid descent and fuel tank inerting can now be studied with simple 1D system level analysis, which allows the engineer to quickly and easily try many configurations and scenarios in a short amount of time.

Finally this final paper showed how leveraging 3D CFD can add robustness and fidelity to a 1D system model by characterizing complex components and then automatically importing them into the Simcenter Flomaster model.

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