Design Validation using Simulation and Experimentation - A Case Study of Combat Aircraft Fuel System

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ABSTRACT

Combat aircraft require a very short turn-around time on the ground due to operational constraints. Especially in between combat missions, the aircraft has to be re-armed and refuelled as quickly as possible. This is achieved through Pressure Refuelling, the capability of refilling all fuel tanks through pumping high-pressure fuel from the Refuelling Bowser on the ground (Ground Pressure Refuelling) or even from a Mother Aircraft in the air (Aerial Refuelling). Pressure refuelling is an essential capability of the aircraft as 50% of the ground operation is refilling fuel tanks. The challenge in designing this system is its seamless operation with the fuel tank venting system. Improper sizing of these systems lead to pressure rise in fuel tanks, which leads to increased refuelling time, damage to the structure and loss of sealant integrity. Also, transient phenomena such as valve operations produce surges in pressure that affect the fatigue life of the system and must be properly quantified. The present study details the process of upgrading a combat aircraft fuel system to enable single-point pressure refuelling. The design process begins by integrating complex component characteristics into a single simulation model using a 1D flow software called Flowmaster (from Mentor Graphics Inc). The simulation results are compared with the rig level test results for improvements and validation. The validated model is further being used for the development of aerial refuelling system. With the modified system, refuelling time is reduced from 1 hour to 10 minutes for filling 4000kg of fuel. The pressure build up in the fuel tanks are also reduced from 10psig to 2psig. The inclusion of simulations reduced the development time and the methodology used in this study is generalised to design the fuel system of future combat aircraft programmes.

KEY WORDS

Pressure refuelling, Ground turn-around time, flow analysis, pressure surge, 1D-simulation.

1.0 INTRODUCTION

Combat aircraft require a specialised fuel system due to various constraints like limited space and irregular tank shapes. For refuelling operations, the dominant constraint is the time taken. Beyond the standard requirement set by the user, any reduction in the refuelling time would greatly increase the effectiveness of the aircraft, since refuelling is a major part of ground operations. This necessitates the use of pressure refuelling, where fuel is pumped at high pressure into a single connecting point on the aircraft. The fuel system pipelines need to be sized appropriately to withstand the resulting high flow rates during refuelling. The alternative system of "gravity refuelling", where fuel is simply poured in through an open hole in the tanks, is retained as a redundancy. Since this is a low-pressure refuelling system and each tank would have its own refuelling port, the time taken to refuel the aircraft is higher by almost an order of magnitude.

Another requirement for modern combat aircraft is the ability to refuel in-flight. This feature enhances the operational range of the aircraft while providing more combat capability, since external fuel tanks can now be replaced with additional weapons. Similar to ground pressure refuelling, aerial refuelling must be completed as quickly as possible, which necessitates a high-pressure/high-flow rate approach. Hence, the design of the pipelines depend on the pressures endured by the system during pressure refuelling (ground and aerial).

The design of the pressure refuelling system must also account for surge pressures or "water hammer" effects during transients in the system. This surge pressure can cause drastic damage to the system if left unchecked. Even if the pressure is within the acceptable load limit of the pipe material, the sudden pressure spikes reduce the fatigue life of the system, since refuelling is a regular process over the lifecycle of the aircraft. Considering these requirements, this paper examines the development, testing and validation of the pressure refuelling system in a combat aircraft.

2.0 FUEL SYSTEM

There are two different fuel systems in an aircraft. The first is the aircraft fuel system, which is a low pressure system of tanks, pipelines, etc., while the other is the engine fuel system, which is a high pressure system within the engine. This study focuses on the aircraft fuel system. The main objective of the aircraft fuel system is the continuous supply of fuel to the engine in all flight conditions. This is achieved through coordinated functions of various fuel subsystems like pressure refuelling system, fuel transfer system, fuel tank venting/pressurization system and fuel quantity management system. The fuel system must also integrate with avionics, flight-controls, electrical and other aircraft systems to automate functions like fuel-transfer, c.g.-management and pilot warnings. A depiction of the fuel system model is displayed below in Fig.1. This system model was developed using a software called Flowmaster (Mentor Graphics Inc.), which is further used to perform parametric studies and simulations. Details of the model is explained in the following sections.

2.1 Pressure Refuelling System

The pressure refuelling system (indicated as red lines in Fig.1) is a network of pipelines designed to handle high flow rates with controllable valves to control the sequence of filling the tanks. During pressure refuelling, the fuel flow rates to the individual fuel tanks depend on parameters such as pressure at the inlet of aircraft refuelling point, resistance in the refuelling line and resistance developed in the venting line of individual fuel tanks.

2.2 Fuel Tank Venting System

The venting system (shown as blue lines in Fig.1) operates in synchronisation with the pressure refuelling system to prevent off-design pressures in the fuel tanks.

The fuel tank venting system seeks to protect individual fuel tanks from excess differential pressure experienced during pressure refuelling and during steep climb/decent manoeuvres performed by the aircraft. The venting system should ensure adequate flow of air into /out of the aircraft fuel tanks with minimum restriction/pressure drop. This leads to less pressure build up in fuel tanks.

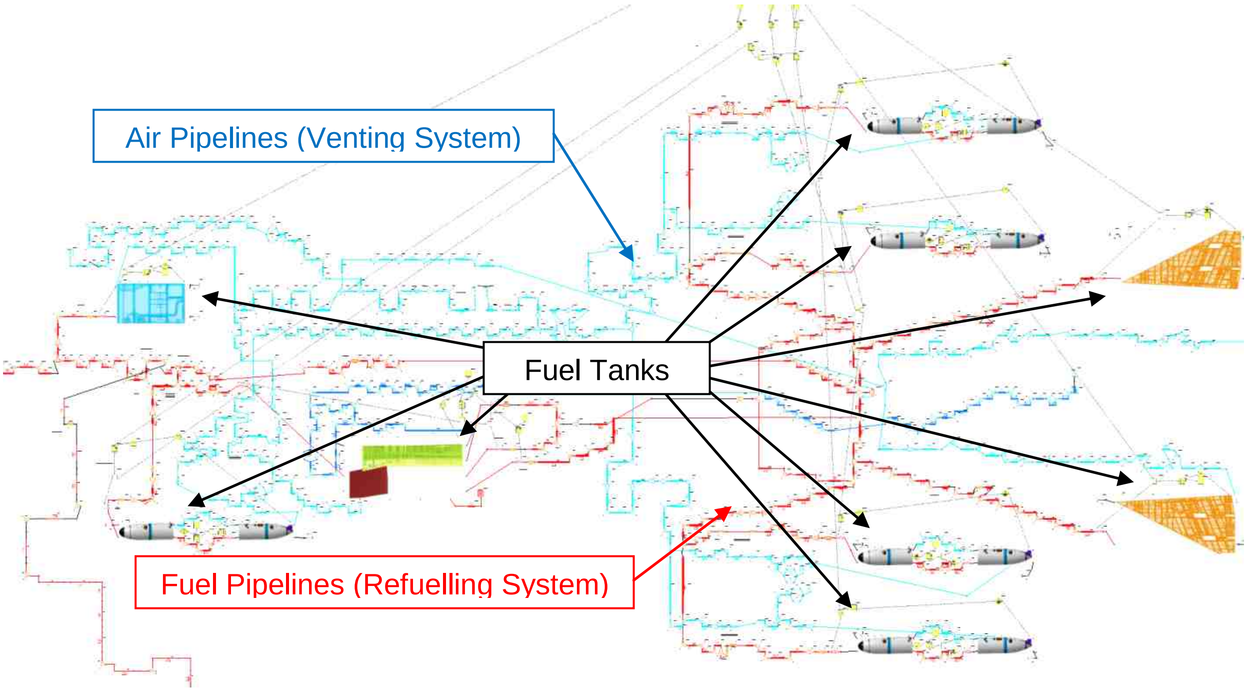

Figure 1 - Simulation Model of Proposed Fuel System

3.0 METHODOLOGY

The development of an aircraft fuel system can be done purely based on prototyping and testing; but, this method is prohibitively expensive and time-consuming. Most modern design projects are primarily based on modelling and simulations, which are further validated using experiments and testing. This reduces the development time considerably since changes can be implemented in computer models much faster than in physical ones. Following this methodology, a computer model was created to simulate the pressure refuelling system. There are several methods to estimate the pressures in the system, including CFD (Computational Fluid Dynamics) simulations.

The methodology of designing a system has changed in recent years to include more streamlined simulations. While the advent of more powerful computers do render complex computations feasible or even practical, it is still in the interest of the designer to streamline the process to be less time-consuming. For example, the computational cost of performing full 3D CFD simulations on the entire fuel system is still high enough to warrant more efficient approaches. One such approach is to combine 3D simulations at the component level with a 1D model at the system level, as shown by Grose[1]. Similar studies of refuelling systems were performed by Ng[2] using the same Flowmaster software.

The components in the fuel system can be simplified by considering only their effects on the pressure refuelling system. In other words, ignoring all other irrelevant data, the components are characterised by a "pressure loss vs. flow rate" curve. The data points for this curve are obtained by CFD simulations and experimental testing (at the component level). This simplified model of each component is then fed into the 1D model of the system.

3.1 System Performance Analysis

At the system level, it is reasonable to assume that radial variation of pressure in the pipelines is minimal. This reduces complex 3D calculations into more manageable 1D equations that govern the flow and pressure in the pipes. The governing equations for solving the pipe network are conservation of mass (flow balancing) at a junction and conservation of energy (pressure loss) between junctions. The inlet of refuelling line and outlet of venting line are applied with pressure boundary conditions. The transient flow simulation is carried out after studying the time step sensitivity. Initial contents in the tank are specified before the simulation. The governing equation[3] for determining the pressure loss due to friction in a straight pipe is:

$$\Delta P = f\frac{L}{D}\rho\frac{U^2}{2} \qquad (1)$$

where,

ΔP = Pressure Loss,
L = Pipe Length
D = Pipe Diameter,
U = Mean velocity,
ρ = Density of the liquid,
f = Friction Factor

The friction factor was initially calculated using the Colebrook-White[3] equation with a smooth pipe assumption. The sensitivity of friction factor is also studied to further refine the model. Similarly, other relevant loss coefficient equations taken from Miller[4] were implemented in the model.

The previous refuelling system of the aircraft experienced considerable pressure build up in the fuel tanks during pressure refuelling trials. To identify the root cause, the 1D simulation model was developed in Flowmaster software emulating the existing system. After running complete refuelling simulations at various inlet pressures, the pressures at various nodes were measured and analysed. Based on the analysis and rig level tests, the system was modified at critical points. The modified system performance is analysed using the updated Flowmaster model for its effectiveness.

3.2 Experimentation on Test Rig

The aforementioned analysis was also complemented by experimentation on an independent fuel tank test rig as shown in Fig.2. This setup was required to capture the complicated filling process taking place in the wing tank which was leading to pressure rise in the tank.

The test rig was also used to measure surge pressures during rapid changes in the system. This "water hammer" effect is further explained in the following section.

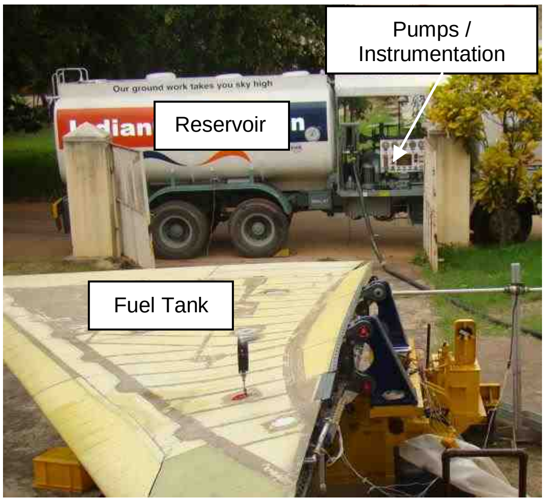

Figure 2 - Wing Tank Test Rig

3.3 Surge Phenomenon

The system responds to sudden changes in fluid flow by rapid pressure fluctuations before settling at a new pressure. While the magnitude of the peak pressure depends on the initial disturbance, the system characteristics govern the dissipation of surge.

The equations governing surge phenomena are relatively simple to calculate for a single wave. But, the reflections of the pressure waves quickly complicate the calculations. Especially in this fuel system with multiple tanks and branching pipelines, the waves are reflected at different times due to length differences in the pipelines. This creates a complex and changing waveform which is a superposition of reflected waves at different time intervals. Since computer simulations can easily handle these types of calculations, as demonstrated by Parks[5], the Flowmaster model was used to simulate these pressure waves.

To illustrate, an enlarged view of the pressure vs. time curve is provided in Fig.3 below, which is taken from one of the simulation results. Note that, while the first cycle appears regular, subsequent cycles quickly resemble noise as more wave reflections are superimposed. Running surge simulations on the existing model was computationally expensive, which imposed several rounds of optimizations in the model.

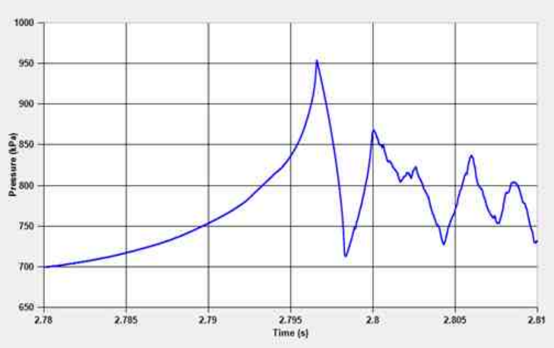

Figure 3 - Enlarged view of Surge Pressure Peaks

The model was optimised for transient calculations using several assumptions. The first assumption was that the effect of the venting system would be negligible for fast transients in the refuelling lines. Hence, an effective back-pressure was added as a boundary condition, simulating only the fuel lines. The back pressures for each tank was calculated by simulating the flow conditions just before the occurrence of system transients, and measuring the node pressure at the exit of each tank.

The pressure waves were calculated in 1D, assuming radial variations in pressure to be minimal. A limitation posed by this assumption is that local pressure spikes in bends are not fully captured in 1D calculations. Instead, the information published by Yang et al.[6] is used to scale the results in only the bend regions. This effectively acts as a local factor of safety for surge prediction near pipe bends. On the other hand, this assumption allows for considerable simplification of the model by combining sections of straight pipes into single pipes of equivalent lengths. Also, the bends in between the straight sections were added at the end of the combined pipe segment. This decreased the computational cost by orders of magnitude. The final model optimized for surge simulations is displayed below in Fig.4.

The major transients in this combat aircraft fuel system are caused by the operation of the refuelling valves. The speed of valve closures directly affect the resulting surge pressures. But, the surge also depends on the type of valve closure, which is characterised by a "Valve Opening vs. Time" curve.

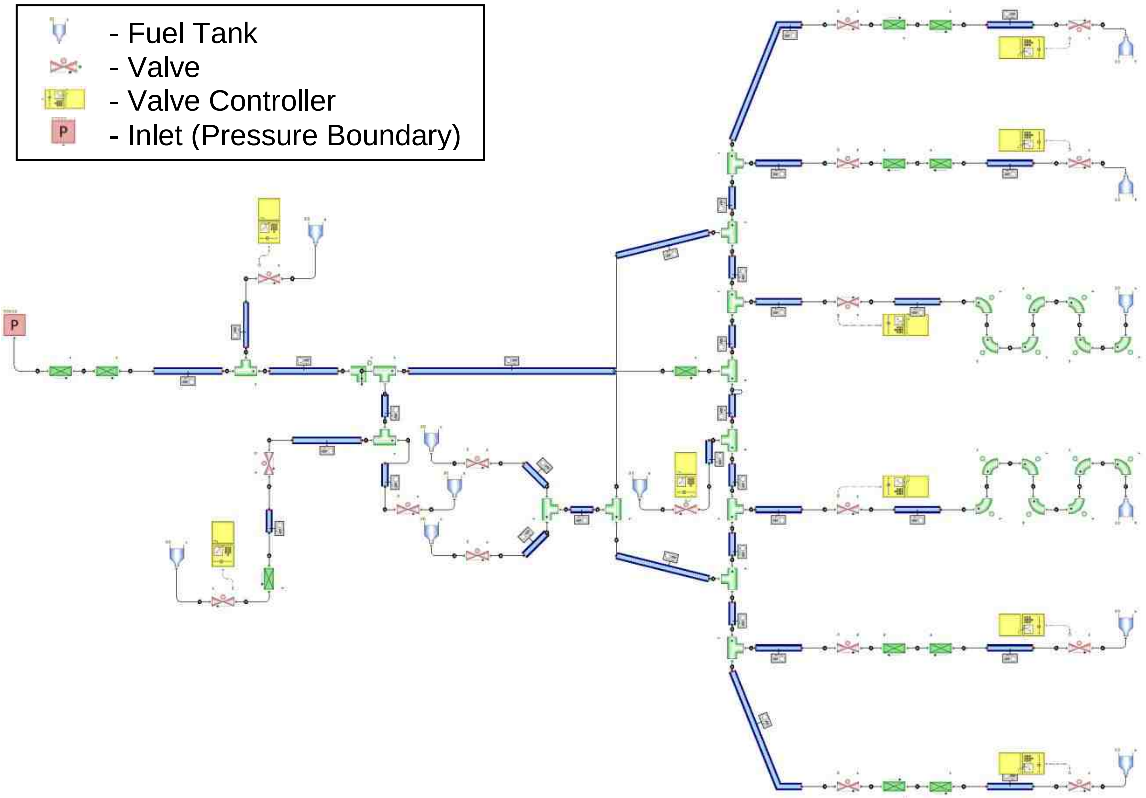

Figure 4 - Model optimised for Surge Simulations

The A sample curve is displayed below in Fig.5. The magnitude of surge depends on the slope (indicated in red) of the curve when the valve is completely closed (i.e., V.O. = 0%). Hence, the refuelling valves in the system are characterised using experimentation and the resulting Valve Opening vs. Time curve is entered into the simulation model.

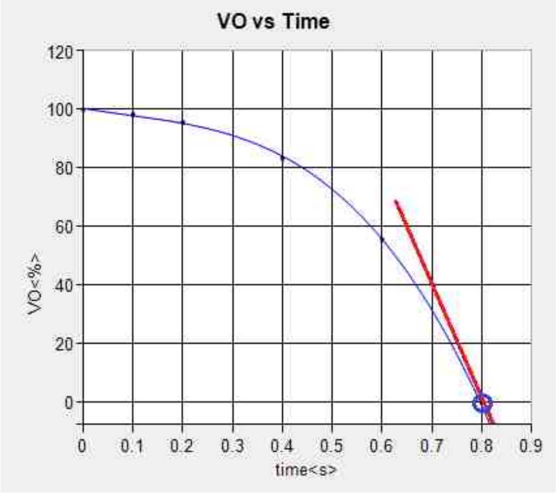

Figure 5 - Valve Closure Curve

Using this information, the model was updated to simulate the surge pressure in an "Incompressible Transient" simulation, where the fluid acts as the medium for propagating pressure waves. The magnitude of the waves depend on the initial disturbance, specifically, the valve closure curve like the one displayed above in Fig.. The wave speed was calculated according to Equation-2 given below:

$$a = \sqrt{\frac{1}{\rho\left(\frac{1}{K} + \frac{DC}{tE}\right)}} \qquad (2)$$

where,

a = wave-speed
K = Bulk Modulus of the liquid
t = Wall thickness
E = Young's Modulus of the pipe
C depends on Poisson's Ratio and the pipe restraint factor.

In parallel, the surge pressure was directly measured using pressure transducers with a high frequency response. This experiment was conducted along with the ground pressure refuelling trials, where additional sensors were integrated into the refuelling lines. The result of these experiments were used to validate the simulation results.

The validated surge model was then used to predict surge pressures at higher initial/operating pressures. Using the results of these simulations, the fuel system was modified so that the adverse effect on fatigue life is within acceptable limits.

4.0 RESULTS AND DISCUSSION

4.1 System Performance

For performance analysis at the system level, the main parameters of interest are the time histories of fuel flow rate, tank pressure and tank contents. The primary parameter which affects the system performance is the pipe friction factor. Sensitivity of friction factor is studied using the simulation model. The data from the ground pressure refuelling trials were compared with the simulation data for fine-tuning the optimum friction factor. This parametric study of friction factor helped in creating a more realistic model of the system.

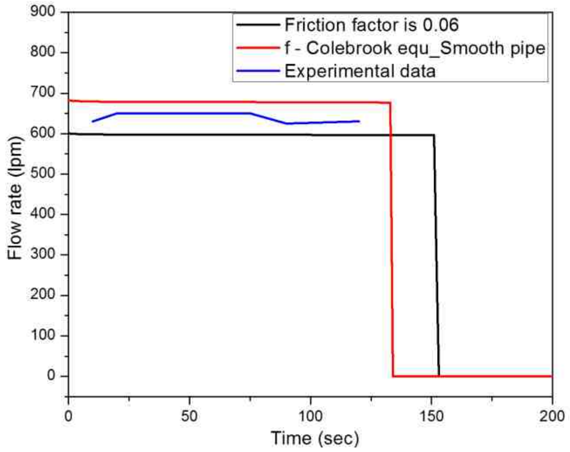

Figure 6 - Refuelling Flow rate Time History

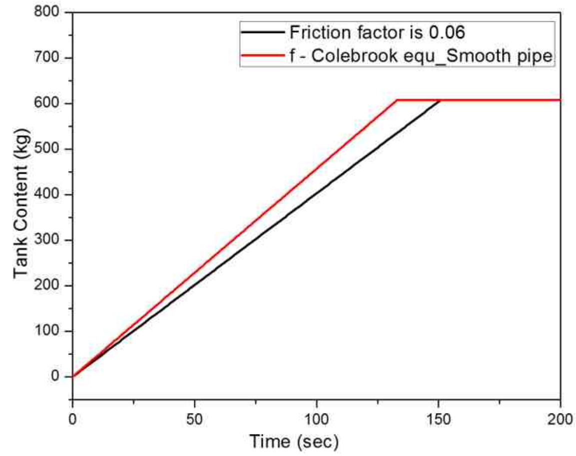

Figure 7 - Tank Content Time History

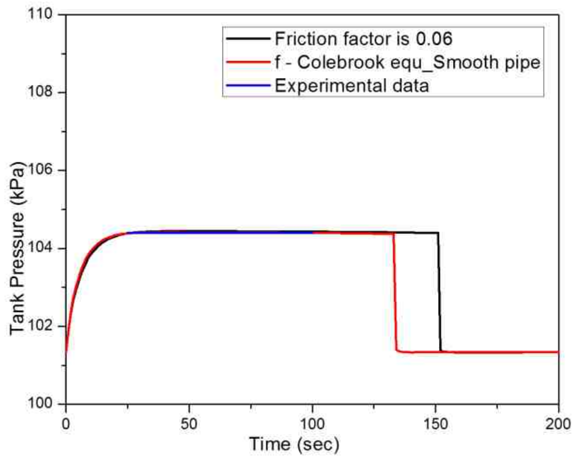

Figure 8 - Tank Pressure Time History

Fig.6 shows the time history of fuel flow rate for various friction factor cases compared with the experimental data of 5 experiments (Experimental data is not the time history of flow rate but discrete flow rates recorded during refuelling trials and varied slightly between the trials). Fig.7 depicts the fuel content increment with time. Since the fixed friction factor of 0.06 produces higher pressure drop, the flow rate is reduced and, in turn, the filling time is increased. Fig.8 shows the time history of tank pressure for various friction factor cases. There is no appreciable variation observed in fuel tank pressure history for different friction factor cases. The ground pressure refuelling trials data are overlapped on the simulation results to find the optimum friction factor value to be used for further analysis. It can be observed from the figures that friction factor of around 0.04 has minimum deviation from the trials data.

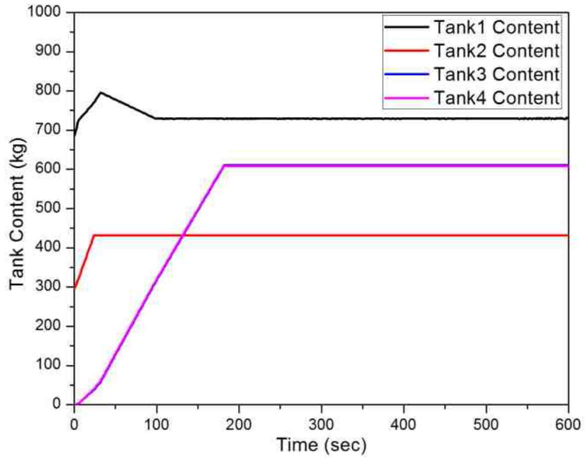

Figure 9 - Tank Content vs. Time

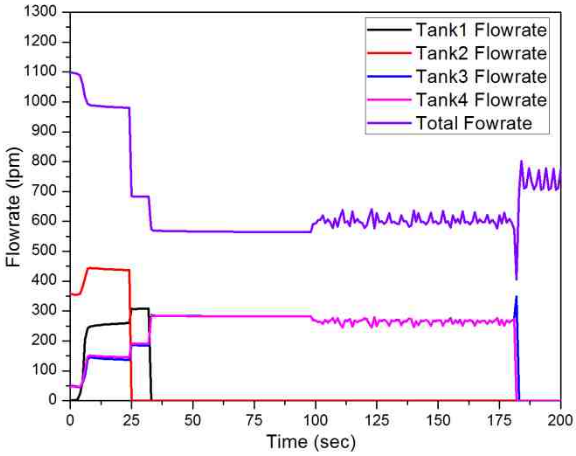

Figure 10 - Flow rate vs. Time

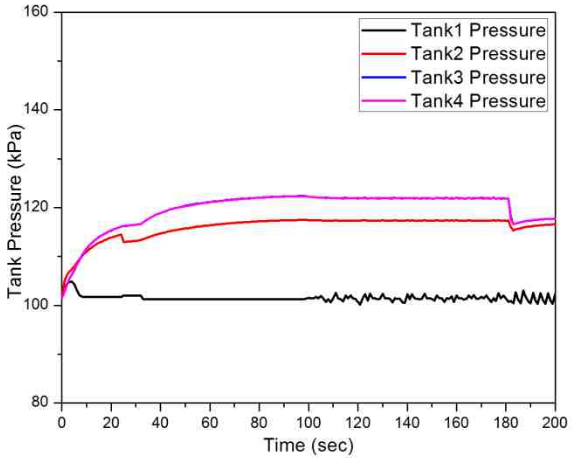

Figure 11 - Tank Pressure vs. Time

The sample plots of predicted performance of the aerial refuelling system are shown in Fig.9 through Fig.11 for partial time duration with f=0.04. The three main parameters studied in the simulation are, tank content, fuel flow rate and fuel tank pressure as functions of time. The variation in the flow rate (Fig.10) is due to the change in system characteristics with time. The fluctuation in flow rate after 100sec is due to the inherent system characteristics with float valve. These fluctuations are reflected in the tank pressure also. Similar simulations are carried out for failure cases expected to happen during actual service of the aircraft.

4.2 Surge Analysis

The results of a surge simulation representing a valve closure is displayed below in Fig.12. The two relevant pieces of information gleaned from the plot are the peak pressure and the settling time (time taken to achieve steady state).

For comparison, the surge pressure data from one of the ground pressure refuelling tests is superimposed with the simulation results.

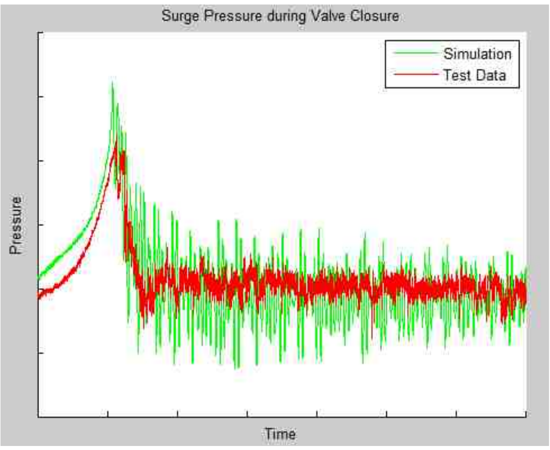

Figure 12 - Surge Pressure Comparison

From the above figure, it can be noted that the difference between simulation and experimental results is within reasonable limits. Note that the simulation provides a more conservative estimate than the measured results, which improves the confidence level of future simulations using this model.

5.0 CONCLUSION

The pressure refuelling system was developed using modelling and simulation methods, which were validated using experiment data. This methodology has reduced the development time significantly and set a precedence for future development projects. The aircraft now meets the performance requirements of pressure refuelling. The same method is used to develop the aerial refuelling system, where a number of critical bottle necks were identified and mitigated before the prototyping phase.

The use of modelling and simulation in the refuelling system development has given confidence for developing advanced fluid systems for future projects. The same methodology is applied in designing all other subsystems of the fuel system.

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