STUDY ON DELIVERY BEHAVIOUR OF SIMMS-FUEL PUMP WITH VARIABLE FREQUENCY DRIVE (VFD)

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ABSTRACT

This project uses a model simulation and analysis approach on a standalone mechanical fuel injection (MUI) system which detached from an engine located at Marine Workshop B20, UniKL MIMET. The subject of choice is a plunger-type reciprocating fuel pump that initially used a camshaft to deliver fuel to the engine and can be retrofitted onto light diesel internal combustion engines (ICE). As a simulation, the pump is connected to a single-phase AC motor 220 V rated at 1.8 kW via a coupling connection instead of a traditional engine. When the electric motor rotates, the shaft drives the fuel pump plunger reciprocally. This project intends to solve the problem of uneven fuel delivery. In these instances, the cause is the inconsistent rotation per minute (RPM) of the electric motors. The problem may be solved by adding a moderator, Variable Frequency Drive (VFD) electronic linked to the motor, which will regulate (limit) the current flow of specific frequency. SolidWorksTM software is extensively used to design the pump cylindrical chamber via a 3D modelling approach. The designed model is then simulated and analysed using ANSYS FluentTM software at different shaft driving speed RPM. The project aims to explore the relationship of driving speed variations RPM with the fuel pump discharge pressure, velocity stream and flowrate. From simulation, it is obtained that SIMMS-fuel pump capable to generate 4.08 MPa to 14.33 MPa and deliver 15.62 g/s to 29.22 g/s at 500 RPM to 3000 RPM respectively which concludes the increasing of driving speed RPM indeed cause increasing of discharge pressure and velocity of the fuel.

Keywords: Fuel Pump; Mechanical Fuel Injection (MUI); Shaft Driving Speed RPM; ANSYS Simulation; Computational Fluid Dynamic (CFD).

1.   INTRODUCTION

Internal combustion engines (ICE) have been quite popular in automotive mobile, maritime, and stationary applications over the last few decades. Referring to the maritime shipping industry, dependability and efficiency of diesel fuel pump are essential to the engine's smooth operation and ability to generate the required amount of power while maintaining fuel economy and low emissions. For choosing the right fuel pump for a specific application, factors such as engine size, fuel type, and operating conditions must be carefully considered. Any malfunction or failure of the fuel pump can result in a reduction of power or insufficient power generation, leading to increased fuel consumption and emissions thereby affecting the operational efficiency of the engine. Thus, the engine is required to exert more effort to generate the same amount of power, which could potentially increase fuel consumption. Understanding the various factors that influence fuel pump delivery behaviour is critical for ensuring optimal performance and longevity, [1]. Therefore, studying the delivery behaviour is necessary to understand the performance and quality of combustion. Fuel delivery systems have become more efficient and dependable on advanced technology. Modern fuel pumps with ECM and sensors adjust fuel delivery rates in response to changes in engine load or speed, increasing fuel efficiency and lowering emissions, [2]. Additionally, advances in materials science have allowed for the creation of pumps that are more durable and long-lasting due to their increased resistance to wear and corrosion. The determination of fuel pump delivery behavior is heavily influenced by usage patterns. Proper pump usage can help extend the pump's lifespan and ensure optimal performance by maintaining appropriate fuel levels, reducing idle time, and performing regular inspections. In contrast, improper usage such as overloading the engine, exceeding recommended speed limits or using low-quality fuel can lead to decreased efficiency or even damage to the

fuel pump. Next, a well-designed fuel delivery system should consider factors such as the fuel delivery rate, pressure and the fuel flow path, [3]. Lastly, regular maintenance is necessary to ensure the correct operation of fuel pumps. For example, the maintenance includes routine inspections, cleaning and the replacement of worn-out or damaged parts. Regular maintenance can help identify potential problems early, preventing costly repairs or replacements in the future, [4], [5]. Technology, usage patterns, system design, and maintenance all play an important role in the delivery behaviour of fuel pumps. This is support by an article that stating regular maintenance, proper usage, and a well-designed fuel delivery system are required for optimal fuel pump performance, [6]. This project considers an actual problem related to the automatic regulation of inconsistent RPM of diesel engine fuel pump camshaft on an operating engine. This may be caused by the occurrence of highamplitude oscillations in the control rods due to moderator malfunctions, which can alter the fuel supply and, in some cases, interfere with the operation of the entire pump section [7]–[9]. However, the diesel engine's technical performances are solved by fitting an additional moderator to control the driving speed of the vehicle's diesel pump camshaft. Frequent maintenance and examination of the fuel pump and motor can also assist in avoiding difficulties and maintaining long-term smooth functioning. The problem then may cause delivery pressure fluctuations which can cause a range of problems for the engine. Inconsistent fuel delivery pressure can result in reduced fuel economy as the engine may not receive the fuel needed for efficient combustion. If the delivery pressure gets too low, the fuel pump will work harder to supply enough fuel to the engine resulting in poor performance. If the pressure is higher than the recommended level, the fuel pump may be subjected to stresses that exceed designed capability resulting in premature wear and failure. Fuel system components including but not limited to fuel injectors, fuel regulators and fuel lines are vulnerable to damage in the event of significant pressure fluctuations over time. Consequently, the fluctuations cause the engine to run lean or rich leading to poor acceleration, rough idling and overall reduced performance.
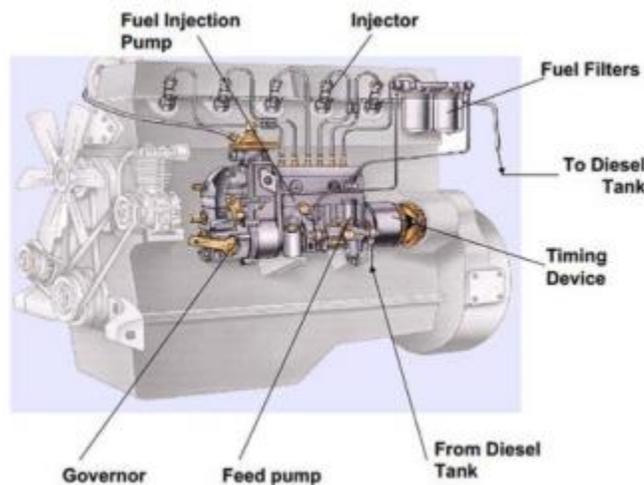

Figure 1: Fuel injection system

The basic design of the fuel pump generally includes a fuel injection pump, a governor, timing device and a set of injectors as figure above. The fuel pump draws fuel from the tank and delivers it at high pressure to the injectors. The control rack ensures that the correct amount of fuel is pumped allows for precise control of the timing and amount of fuel injection. However, the SIMMS-Fuel Pump for this project is a standalone component which detached from an engine. This project proposes a VFD as a speed controller to refurbish the pump to control the RPM for experimental use. The proposed solution is further validated by a study using VFD to control AC motor of generator rated at 500kW (idling at 300rpm). The study successfully reduces the GHG by 15 percent and increase the fuel saving by control the shaft driving speed of motor, [10]. Another study uses difference approach of MATLAB-based method for designing an effective speed controller for a fuel pump, [11]. By adjusting the pump's speed, the amount supplied is manipulated. The objective is to regulate the 3 phase AC motor's torque. Nevertheless, the idea of controlling the driving speed of motor using a controller showcase practical solution to overcome the problem stated. Referring to modern diesel engine, the engine control module (ECM) control real-time of few aspects of the engine's functioning including fuel injection, ignition timing and emissions control. Knowing how the moderator work and their roles in engine operation can help identify and troubleshoot any issues that may arise, leading to better engine performance, efficiency and a longer lifespan of components.

An approach using Computational Fluid Dynamics (CFD) on a numerical model will be established to analyse the working behaviour of the fuel pump injection. CFD methods allow engineering designers to obtain more qualitative and quantitative information about condition behaviour systems by investigating flow patterns inside pumps, [12]. The outcomes of numerical calculations can provide reasonably accurate data about the trend of fluid flow in various types of pumps. One study conducted a CFD to design, modelling and simulate a fuel pump for GDI system that may retrofit onto spark ignition (SI) engines. Author designed the fuel pump by using SolidWorks software and analyse the fluid flow by using ANSYS Fluent and found the close agreement to the preliminary design parameters of GDI pump. The results of the study showed that improve the efficiency of the engine, the fuel pump driven by an external DC motor; relieving the engine in providing the auxiliary power supply, [3]. Another study uses the CFD to simulate a newly developed HPP system for small engine operate at a constant speed. The pump model is developed in accordance with a physical model-based design approach and simulated using Matlab- SimscapeTM. Based on the calculation and simulation performed, the designed pump pressure is capable of producing discharge exceeding 4.5 MPa. When the same condition is applied to the physical modelling simulation using MATLAB, the pressure developed by the pump is 11.15 MPa – indicating an error of only 5.8 percent, [13].

The significance of this research project lies in the investigation of the effects of malfunctioning fuel pumps on uneven fuel delivery for MUI system. The project aims to understand the relationship between fuel pump speed variations RPM and its impact on fuel delivery by simulating the fuel pump's delivery behaviour using ANSYS Fluent software. This provide in-depth understanding of relationship between fuel pump driving speed variations RPM and its impact on fuel delivery. Moreover, the project's investigation of using VFD as a moderator to regulate motor RPM can lead to practical solutions that can enhance the reliability and efficiency of fuel pumps in real-world applications. The implementation of speed controller-moderator systems has surfaced as a potentially effective method for regulating engine speed and enhancing fuel pump efficiency through the continuous monitoring of engine speed and the regulation of fuel delivery. Furthermore, the literature points out the importance of appropriate fuel system design, maintenance plan and usage patterns in optimizing fuel pump effectiveness and durability. The literature also prove CFD has theoretical instrumental in optimizing fuel pump design and analysing fluid flow characteristics which subsequently associated with engine efficiency. In order to address the problem of uneven fuel delivery resulting from inconsistent motor rotation speeds, it is necessary to take into account the malfunctions factors associated with the moderator. In the case of AC motors, adding VFD can result in consistent and controlled fuel delivery, thereby resolving the problem of inconsistent RPM.

The SIMMS-Fuel Pump with Variable Frequency Drive project aims to conceptualise, develop, and implement a fuel pump system that uses variable frequency drive (VFD) technology. Therefore, this research project said to contribute to improving the performance and reliability of fuel pumps in various applications leading to more sustainable and cost-effective operations. Nevertheless, the result of this project is to acquire comprehensive research on delivery behaviour. The fuel pump driving speed is the only adjustable parameter. SolidWorks software is extensively used to design the pump via a 3D modelling approach. The designed model is then analysed using ANSYS Fluent software. The variable of piston driving speed will be used as the input and meshed during the simulation process. The simulation condition, incompressible flow, slip boundary condition, plunger stroke, suction and discharge process will be considered during the fluid flow simulation of the 3D model [3], [14]. The project report will further discuss the relationship of speed variations with its working pressure, in-cylinder velocity stream and pressure distribution by analysing the simulation and recorded data.

2.   RESEARCH METHODOLOGY

This research is project based on simulation values from CFD techniques. The standalone SIMMS-fuel pump with plunger type of MUI system, AC motor and VFD were selected. The specification of fuel pump chamber parameters and values is shown in Table 1. In this experiment driving speed RPM was used to investigate the relationship of driving speed variations RPM with the fuel pump discharge pressure, velocity stream and flowrate. The VFD was electronically linked with the prime mover of the fuel pump, AC motor. The VFD takes a fixed AC voltage and frequency and converts it to DC using a rectifier bridge, filters the DC with a capacitor bank and inductors, then inverts the DC voltage back to AC and sends it to the motor at the desired frequency. By varying the desired frequency, the speed of AC motor is now controllable. The variable parameters (shaft driving speed) will be used as the inputs and meshed during simulation process in software. As a function of variable driving speed of the driver, the parameters will be displayed on the VFD. For instance, as the motor's rotation per minute (RPM) increases, the fuel delivery increases, leading to a higher-pressure supply reading inside the pump. It should be noted that the plunger is driven by the coupling and moves reciprocating in the cylinder.

Table 1: Fuel pump chamber parameters and values

Parameters	Value
Bore × Stroke	10×0 mm
Discharge Pressure	4 to 20 MPa
Suction Pressure	0.16 MPa
Mass flow rate	Varies in g/s
Motor Speed	Varies in RPM
Number of plungers	Single acting
Pump displacement	2.6182 e-5 m^3/s
Pump Capacity	2.487 e-5 m^3/s
Power input	0.20644 hp
Power Output	0.1764 hp
Working fluid	Diesel

A technical manual of the SIMMS model was referred to develop a model, simulate and analyse the process within the software. This brief approach comprises four important steps, first one contains of pump geometry preparation parts. SolidWorks software will be extensively used to design the pump via 3D modelling approach as figure below.
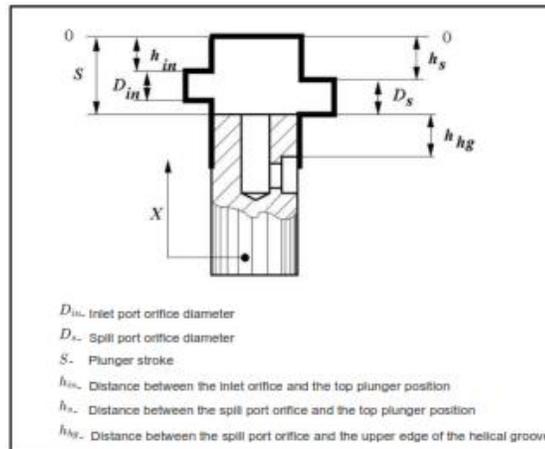

Figure 2: Fuel pump chamber dimensions

The second step is to extract the model to ANSYS Fluent and generate a meshing domain for each portion geometry. The physical features and usual material used by the manufacturer for SIMMS-FUEL PUMP was considered during the meshing process. Third one is important step in this method is setting of solver setup as specifications in Table 2. This step provides that flow property types, chosen variety of boundary conditions, type of turbulence model selecting, mesh parts interfaces, numerical flow schemes and convergence setting controls. The designed model will be analysed using ANSYS Fluent software to simulate the flow pattern (velocity stream) as well as the pressure distribution during pumping process. The final and most important step is to select different types of parameters for monitoring flow (ex. changes of stream velocity due shaft driving speed, discharge pressure values), then run computational calculations for FLUENT and collect stored results throughout the post-processing period. Using the CFD method, the discharge and pressure were compared and verified by changing key parameters.

Table 2: Solver setup settings

Parameters	Value
Working fluid	846 kg/m^3
Cp (Specific Heat)	2193.27 J/(kg K)
Thermal Conductivity	0.1157 W/(m K)
Viscosity	0.0029 kg/(m s)
Pressure	0.16 MPa
Velocity	3.25 m/s
Temperature	300 K
Heat transfer coefficients	Enabled
Wall roughness height	0 mm
K-epsilon model	-

3.   RESULTS AND DISCUSSION

A unit of plunger-type reciprocating fuel pump motion is simulated at different RPM by using ANSYS software and the results is presented. The simulation aimed to investigate the pump's fluid flow delivery (velocity stream and pressure contour) as functions of discharge working pressure at different RPM. The simulation is conducted within the range of 500 to 3000 RPM, with intervals of 500. The simulation results are presented at two distinct piston positions of Bottom Dead Centre (BDC, 0mm) and Top Dead Centre (TDC, 10mm) as in-cylinder pressure contour and velocity stream diagrams at various piston speeds.

3.1   IN-CYLINDER PRESSURE DISTRIBUTION

From the simulation, data for in-cylinder pressure are collected and tabulated as below tabled and plotted in graph.

Table 3 Pressure Distribution at Different RPM Values

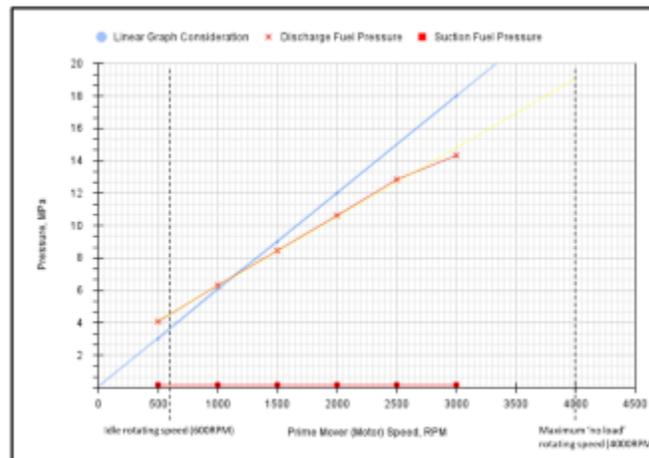| RPM (revolutions per minute)	Discharge Fuel Pressure (MPa)	Suction Fuel Pressure (MPa)
500	4.08	0.16
1000	6.31	0.16
1500	8.45	0.16
2000	10.62	0.16
2500	12.84	0.16
3000	14.33	0.16

Figure 3: Fuel Pump Pressure at Different RPM Values

Based on the simulation, the analysis of the simulation data demonstrated the impact of speed variations of piston on the in-cylinder pressure distribution. The suction pressure remains constant at 0.16 MPa because it is constant value and considered same regardless the driving speed RPM. A unit fuel pump discharge pressure (at the delivery outlet) has a rising trend from 4.08 MPa at 500 RPM to 14.33 MPa at 3000 RPM. This concluded the fuel pump discharge pressure increased as the RPM increased. The rise in pressure is a clear indication of how the system reacts to higher driving speed considering the other variables stay constant, implying a direct relationship between driving speed RPM and pressure output.

3.2   IN-CYLINDER VELOCITY STREAM

From the simulation, data for in-cylinder velocity stream and in-cylinder pressure are collected and tabulated as below tabled and plotted in graph. With given discharge fluid velocity, the flowrate for a unit fuel pump may be determined using the equation. The flowrate (Q) is equal to the product of the discharge velocity (V) and the cross-sectional area (A).

Table 4: Velocity Stream at Different RPM Values

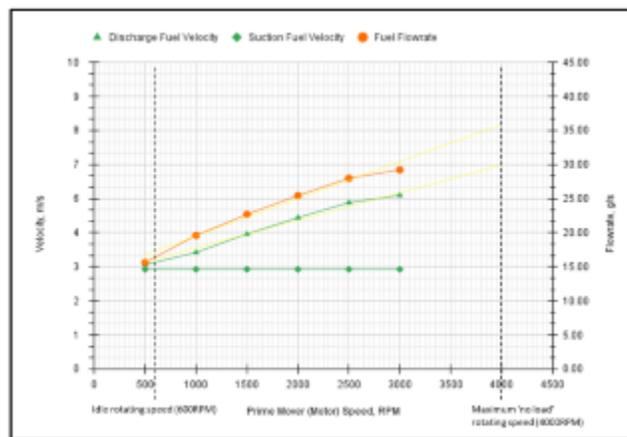| RPM (revolutions per minute)	Discharge Fuel Velocity (m/s)	Suction Fuel Velocity (m/s)	Fuel Flowrate (g/s)
500	3.42	3.25	15.62
1000	3.81	3.25	19.60
1500	4.40	3.25	22.71
2000	4.94	3.25	25.46
2500	5.43	3.25	27.99
3000	5.67	3.25	29.22

Figure 4: Fuel Pump Velocity at Different RPM Values

Concurrently, the analysis of the simulation data also demonstrated the impact of speed variations of piston on the in-cylinder velocity stream. The suction velocity remains constant at 3.25 m/s because it is constant value and considered same regardless the driving speed RPM. It was observed that higher RPM values corresponded to increased velocity stream within the chamber. The discharge fluid velocity, which represents the speed at which the fluid or component moves, shows a significant increase from 3.4 m/s to 5.7 m/s throughout the range of 500 RPM to 3000 RPM respectively. From this value also we can derive the volume flowrate. From the tabulated data, it shows that increasing of RPM resulting in a higher flow rate of fuel into the high-pressure tube. It should be mentioned that the flow rate changes in dependence on RPM while the amount of fluid supplied remains constant,

The simulation illustrates the significant patterns in behavioural changes as the RPM of the prime mover vary. It is noticeable that the speed of the piston in the fuel pump is directly proportional influenced by the RPM of the motor. These data highlight a continuous pattern in which increased RPM of prime mover are associated with higher pressure and velocity in the system. Comprehending and using these connections are crucial for maximising effectiveness, guaranteeing operational security, and possibly adjusting the system for certain performance goal.

4.   CONCLUSION AND RECOMMENDATION

The ANSYS Fluent simulation provided a comprehensive numerical analysis. By logic, when a value is given at 1000 RPM, supposedly it is twice that value for 2000 RPM and higher. However, the actuality does not align with that. The same principle applies to the correlation between pressure and velocity. It has complex mathematical and physics rules. The simulation results highlighted a trendline of significant influence of RPM variations on velocity stream and pressure distribution in the cylindrical chamber. Through simulations, variations in discharge pressure at different piston (pumping) speeds are observed. It is obtained that the fuel pump model is capable to generate 4.08 MPa to 14.33 MPa at 500 RPM and 3000 RPM respectively. According to existing literature, increasing the fuel pressure supplied to injector will then cause shorter ignition and faster burns rate in combustion chamber. For independent MUI system, the discharge fuel pressure is directly supplied to the injector. As a result, a higher pumping rate will give a higher injection rate.

SIMMS fuel pump in this project offers flexibility to be configured for either the MUI system or the common rail system. Should implemented in an actual case, the decision is subjective and will demand additional efforts, given that the complex system have more components and incurs higher costs. Nonetheless, both systems can operate efficiently, each with its own set of advantages and disadvantages for real applications.

Dealing with fuel injection equipment for diesel engines, researchers extensively investigated fluid dynamic behaviour both numerically and experimentally in the last decade, [15]. However, literature concerning the pump is not as rich as the one concerning the injector. Due to the cost, time consumption, and practicability, most studies related with fuel pump have been conducted using software where further discussions on issues concerning future work of experiment data validation may require. Theoretical alone cannot accurately describe actual motion, [2]. The numerical model data trend accuracy is needed to be validated by an experimental data set comparison and analyse of fuel system pressures at different rated near in future. Establishing a test bed and rig would offer precise insights into the arrangement of the fuel pump, validating ongoing research and determining the margin of error between data set.

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