MODELING OF COMMON RAIL FUEL INJECTION SYSTEM OF FOUR CYLINDER HYDROGEN FUELED ENGINE

Mohammed Kamil[1], M. M. Rahman[2], Rosli A. Bakar[3]

[1],[2],[3] Faculty of Mechanical Engineering,
Universiti Malaysia Pahang, 26600 UMP, Pekan, Pahang

Email: [1]mohammedk_22@yahoo.com,
[2]mustafizur@ump.edu.my, [3]rosli@ump.edu.my

ABSTRACT

Automotive system components, such as injection system, which have an increasing number of parameters and new design approaches, are required. It is no longer possible to optimize such a system solely based on experience or forward optimization. Modeling of hydrogen fuel injection system is a very important tool that can be used for predicting the effect of advanced injection strategies on combustion and emissions of a hydrogen-fueled engine using port fuel injection. This paper addresses the modeling of common rail fuel injection system for four stroke four cylinder port injection hydrogen fueled engine. The common rail injection system model has been developed utilizing GT-FUEL commercial software. Focus is paid for the wave propagation phenomena arising in this system subsequent to the injection event and pressure oscillations that influence the injected fuel quantity. One dimensional flow equations in conservation form are employed to simulate wave propagation phenomena throughout the common rail (accumulator). The interaction effect of operational conditions including the engine speed and rail pressure is illustrated. The required compromise solutions are discussed in details. It can be seen that the common rail injection system is a promising enhancement for hydrogen port injection engine.

KEYWORDS: Hydrogen fueled engine, port injection, common rail, wave propagation, rail pressure, engine speed.

1.0   INTRODUCTION

Interest in the hydrogen economy has grown rapidly in recent years. Those countries with long traditions of activity in hydrogen research and development have now been joined by a large number of newcomers. The main reason for this surge of interest is that the hydrogen economy may be an answer to the two main challenges facing

the world in the years to come: climate change and the need for security of energy supplies. Both these challenges require the development of new, highly-efficient energy technologies that are either carbon-neutral or low emitting technologies. Another reason for the growing interest in hydrogen is the strong need for alternative fuels, especially in the transport sector. Alternative fuels could serve as links between the different energy sectors, especially between the power system and the transport sector, to facilitate the uptake of emerging technologies and increase the flexibility and robustness of the energy system as a whole (Larsen *et.al.*, 2004). The comparison of hydrogen properties with compressed natural gas (CNG) and gasoline fuels are tabulated in Table 1.

The unique combustion properties of hydrogen can be beneficial at certain engine operating conditions and pose technical challenges at other engine operating conditions. These challenges include abnormal combustion (pre-ignition, backfire and knocking), and higher heat transfer losses (MacLean and Lave, 2003). Hydrogen fuel can be induced to the combustion chamber either by: (i) external injection (e.g., using port or manifold fuel injection); or by (ii) direct injection to the combustion chamber. Injecting hydrogen fuel directly in the cylinder is not typically accompanied by pre-ignition occurrence and typically has the potential for the highest power. However, it leads to a reduction in the thermal efficiency due to non-homogeneity of the mixture inside the cylinder; and the required compact fuel injection system. Then, hydrogen induction by means of port injection can be considered as a compromise between the sophisticated direct injection system and the uncontrollable carbureted system. As a compromise solution, the design of the port injection should approach as much as possible from the desired features and move away from the undesired. This suggests that extensive studies and enhancements must be achieved with the port injection system.

TABLE 1
Comparison of hydrogen properties with CNG and Gasoline
(White *et.al.*, 2006)

Property	Gasoline	CNG	Hydrogen
Flammability limit (Ø)	0.7-4	0.4-1.6	0.1-7.1
Laminar flame velocity (m/s)	0.37-0.43	0.38	1.85
Research octane number	91-99	140	>120
Adiabatic flame temperature (K)	550	723	858
Stoichiometric volume fraction (%)	~2	9.48	29.53
Minimum ignition energy (MJ)	0.24	0.28	0.02
Quenching distance (mm)	~2	2.1	0.64
Lower heating value (MJ/kg)	44.79	45.8	119.7
Heat of combustion (MJ/kg of air)	2.83	2.9	3.37

Common rail (CR) hydrogen injection system for port injection is proposed in this study to improve the performance of the port injection system. The main key for this enhancement is the flexibility that can be provided for the most important injection parameters: The pressure level generation is almost independent of the engine speed and of fuel metering; the injection timing and duration can be optimized for every working conditions. In diesel engines, the CR injection system has met an extraordinary success and is reasonable of the ever-increasing share of diesel engines in European automotive market (Catania *et.al.*, 2008a). The ability of delivering multiple injections, which is one of the most interesting features of such injection systems, allows an improved combustion and heat release rate control, resulting in clean and efficient engine performance. To achieve this result, CR electro-injectors have thoroughly been investigated by researchers of the automotive field, in order to obtain fast actuations, retaining, at the same time, a good precision of the injected fuel volume (Catania *et.al.*, 2008b). However, the dynamics of CR hydraulic components can cause sensible perturbations to multiple injections, which hence occur under different conditions from those expected. The wave propagation phenomena arising in the system, subsequent to an injection event, lead to pressure oscillations that influence the injected fuel quantity, particularly when the dwell time between consecutive injections is changed. The dependence of the injected quantity on the system dynamics was also pointed by other authors for diesel engines (Bianchi *et.al.*, 2002; Catalano *et.al.*, 2002; Henein *et.al.*, 2002; Mulemane *et.al.*, 2004).

The rail pressure is also affected by the system dynamics: Whenever an injection occurs, the pressure in the rail drops because the rail itself does not behave as an infinite volume capacity (Bianchi *et.al.*, 2002). A sensor for continuously monitoring the pressure at the injector inlet was proposed by (Torkzadeh *et.al.*, 2002) to delivered the information to ECU and thus adjust the injection parameters, so as to better control the injected fuel quantity. In fact all these studies and findings are reported for diesel common rail injection system. It is quite difficult to find a work reports a detailed analysis of CR hydrogen injection system and the pressure-wave propagation phenomena in this system. Numerical models of CR diesel injection system, based on one-dimensional (1D) partial differential equations, were developed in (Catalano *et.al.*, 2002; Catania *et.al.*, 2008b; Ferguson and Kirkpatrick, 2001). However, as per authors' knowledge, no model has been developed for CR hydrogen port injection system.

In the present work, CR for hydrogen injected system is suggested and modeled for port injection hydrogen fueled engine. A one- dimensional

compressible pipe flow model is developed using GT-FUEL code. Using this model, the gas dynamic and pressure wave propagation phenomena of CR injection system were examined briefly; and its response to the variation in several parameters is clarified. These parameters include: engine speed, rail pressure, and injector's holes diameter. It was shown how such a model is capable of predicting the complex flow phenomena that occur in the system.

2.0   MODELING DESCRIPTION

The main components of the suggested CR hydrogen injection system are shown in Fig. 1. Hydrogen tank is used as a reservoir for hydrogen and non-corroding and free of leaks. Openings (safety) valves is provided for excess pressure to escape automatically. Hydrogen tank is situated far away from the engine to avoid ignition of escaping hydrogen in case of accident. A pressure regulator is used to required injection pressure. The injected hydrogen quantity depends upon the injection period and difference between hydrogen pressure in the rail and port pressure. However, in case of return-less hydrogen system (which is suggested in this model because there is neither low pressure tank nor a compressor for re-compressing hydrogen gas) the pressure regulator is a part of in-tank unit. Hence hydrogen rail pressure is maintained at a constant level with reference to the surrounding pressure. This means that the difference between hydrogen rail pressure and port pressure is not constant and take into account when the injection duration is calculated. Hydrogen is supplied to the individual injector with the help of the common rail. Common rail is used for mounting and location of the injectors; storage of the hydrogen volume and ensuring that hydrogen is distributed evenly to all injectors. The electromagnetic injectors (solenoid-controlled) are injected hydrogen into the intake port at system pressure. It permits the precise metering of the quantity of hydrogen required. It is triggered through the engine control unit ECU driver stages with signal calculated by engine management system.
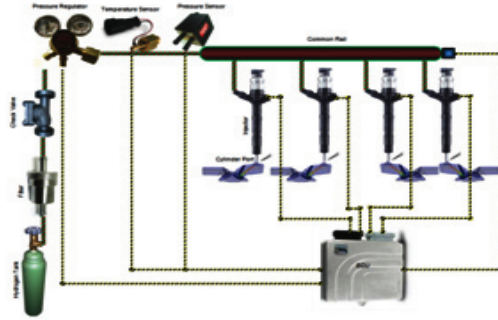
FIGURE 1
CR Hydrogen Injection System

The behavior of the pressure waves is modeled using the equations of compressible gas dynamics. The governing equations for the CR hydrogen injection system are the unsteady mass, momentum, and energy conservation equations, which are expressed in vector form (1-2) (Ferguson and Kirkpatrick, 2001):

$$\frac{\partial f}{\partial t} + \frac{\partial F}{\partial x} = Tf = \begin{bmatrix} \rho A \\ \rho AU \\ \rho AE \end{bmatrix} \tag{1}$$

$$F = \begin{bmatrix} \rho AU \\ A(\rho U^2 + P) \\ \rho AUH \end{bmatrix}; \qquad T = \begin{bmatrix} 0 \\ \tau_\omega \sqrt{4\pi A} + P\frac{\delta A}{\delta x} \\ q_\omega \sqrt{4\pi A} \end{bmatrix} \tag{2}$$

where ρ is the hydrogen density, A is the cross sectional area of the rail, U is the hydrogen velocity, P is the pressure, E is the total specific energy; H is the total specific enthalpy, τ_ω is the wall shear stress, and q_ω is the wall heat flux. There are a number of gas dynamic programs that numerically solve the compressible conservation equations to predict system flow.

GT-FUEL code is used to develop the gas dynamic model of the CR hydrogen port injection system for four cylinder engine. The fuel system components are assembled and to fit the desired behavior of each fuel system component. The underlying physics of the flow is governed by a fully transient, mean-line analysis based on one-dimensional Navier-Stokes equation. The input parameters including engine speed rpm, rail pressure, and injector's holes diameter were defined in the model. There are several ways to model the performance of a component. The first part in the systems is the high pressure hydrogen tank. The temperature of the tank is considered to the ambient temperature, 300

K and composition is pure gas hydrogen. The high pressure in the tank is considered as a parameter. This pressure is reduced to a pre-specified value through the pressure regulator. The latter is modeled simply as an orifice connection between the tank outlet and next tube. The diameter of the orifice is considered as a parameter to control the pressure downstream the regulator. The discharge coefficients are calculated using the geometry of the mating pipe and orifice diameter. This description is followed for the check valves and regulator all over this system. The next part in the hydrogen line is a pipe carries the hydrogen from the tank to the filter. The conduction heat transfer between the pipe wall and hydrogen gas is neglected and the initial temperature of the pipe wall is considered to environment temperature. The filter in the hydrogen circuit removes the solid particles which could cause wear. It is imperative that hydrogen is efficiently cleaned in order not to damage the precision of the injection system. The filter is modeled in this model as a pipe similar to the delivery pipe. However, higher surface roughness is assumed in order to consider the pressure losses in this part. Another two pipes are added to simulate the hydrogen lines. Three flexible pipes are also included in the hydrogen line upstream the rail. The purpose is to investigate the effect of the elasticity of these pipes on hydrogen wave speed. The function of the check valve in the hydrogen line is to ensure that hydrogen flow happens in one direction and no reverse flow.

As stated early, the rail has the task of storing hydrogen and damping the pressure fluctuations as effectively as possible. It is worth to mention that the expected fluctuation for hydrogen rail is lower than diesel or gasoline fuels. This is because the fluctuations of these fuels are introduced by two sources including the pump and injectors. However, there is no need for a pump in the hydrogen system because hydrogen is stored in a high pressure and consequently no pumping pulsations. The flow inside the rail is considered as 1D isentropic flow. The isentropic flow is an adiabatic a flow in which there is no heat exchange) frictionless flow. This means that the effects of viscosity and heat transfer are restricted to thin layers adjacent to the walls, i.e., only important in the wall boundary layers. This assumption becomes more realistic because of gas hydrogen density is very low (0.0824 kg/m^3) compared with liquid gasoline (730 kg/m^3) and that hydrogen is injected in the ambient temperature. Figure 2 shows the configuration of the common rail. The CR is modeled using a series of pipes and flow-splits. Four flow-splits, connected by three pipes, are composing the rail. The flow-splits are composing from an intake and two discharges. The intake draws hydrogen fuel from the preceding flow component (pipe). One discharge supplies hydrogen to the next pipe and other

supplies hydrogen to the injector. The discharge of the last flow-split is closed with cup to prevent any flow through it because there are no more flow components. Conservation of momentum is solved based in 3-dimentional flow-splits even though the flow in GT-FUEL is otherwise based on a 1D version of the Navier-Stokes equation. The characteristic length and expansion diameter are defined for each port in the flow-split. The characteristic length is the distance from the port plane to the opposite side of the flow-split (used in to calculate the propagation of pressure waves through the flow-split). The expansion diameter is used in calculating the kinetic energy losses due to area expansion inside the flow-split. Figure 3 shows the geometry of flow-split no. 1. The sensors and monitors are equipped in the rail to sense and monitor the variations in pressure and temperature with crank angle throughout the run session. These are fixed in flow-split no. 4 and pipe no. 2 of the rail respectively.
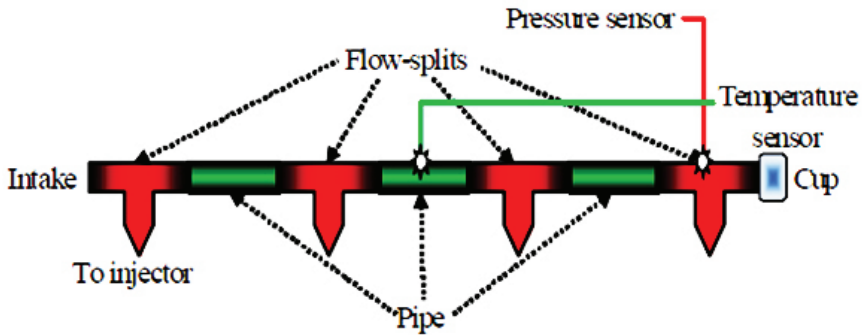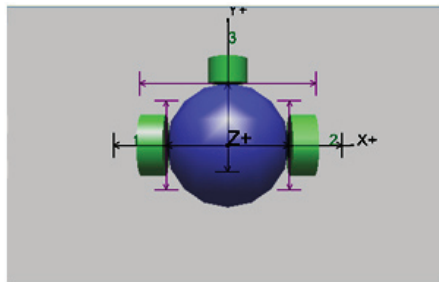

FIGURE 2
Common rail configuration

FIGURE 3
Geometry of flow-split

In the present model, the fuel injector motion (opening and closing) is prescribed instead of being calculated. The opening and closing profiles of the injectors are imposed using pipes and orifices to model the injectors and orifice represents the injector holes. The opening

and closing of the injector is controlled through the orifice diameter. The orifice diameter is defined as a function of the main drive (crank shaft) angle. This simplification is done because the focus of this study is on the gas dynamic phenomena in the common rail. Each injector is considered four holes. Figure 4 shows the developed common rail model for hydrogen fueled engine utilizing the GT-FUEL codes.
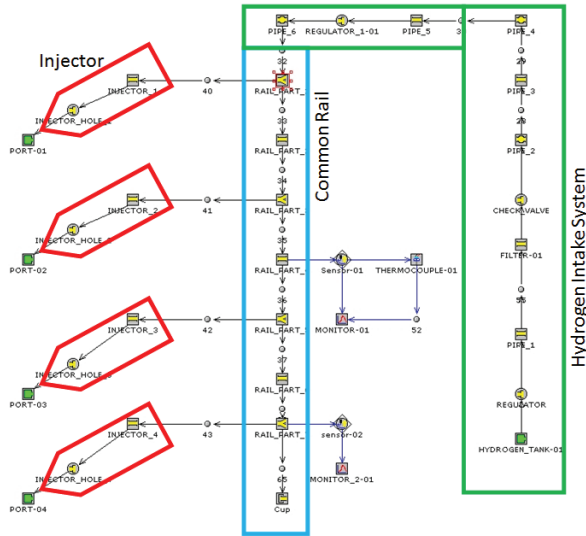

FIGURE 4
GT-FUEL Model approach setup for the CR hydrogen injection system

3.0   RESULTS AND DISCUSSION

In this section the results obtained from the developed model will be analyzed. The results are focusing on the wave propagation and gas dynamic behavior of hydrogen gas flow in four strokes four cylinders port injection engine. The effects of engine speed, rail pressure injector holes diameter will be investigated. The present section is subdivided into three parts to highlight the trends with each of the above stated parameters. Young modulus for flexible pipes is 200 GPa, single injection event, and the results are for cycle no. 5 conditions are adopted in the model.

The flow in common rail is unsteady due to the periodic injectors opening and closing. The opening and closing of the injector creates finite amplitude compression and rarefaction pressure waves that propagate through the common rail hydrogen flow. These pressure waves may aid or inhibit the hydrogen exchange processes. Therefore

the size of the common rail necessity to tune properly to obtained the preeminent gas exchange. The effect of engine speed on gas dynamic of hydrogen flow is investigated. The engine speed of 3000, 4000 and 5000 rpm were considered in this investigation. The results presented are 0.5 mm injector holes diameter and 3 bar rail pressure.

Figure 5 shows the pressure variation in the common rail with crank angle for different engine speed. The complexity of the phenomena that occur is apparent. The amplitude of the pressure fluctuations increases substantially with decreasing engine speed. Maximum amplitude of 0.047 bar was reported at 3000 rpm, while the maximum amplitude of 0.032 bar happens at 5000 rpm. However, as the engine speed increase, the frequency of the pressure waves increases. The rapid closing of the injectors results in high oscillations waves known as the "water hammer effect" which can be seen clearly in figure 5. Higher speeds lead to higher number of closing and opening times for each injector and this is reflecting in higher frequency for the pressure pulsations. Each injection triggers a pressure wave in the rail. This wave influences the fuel quantity of the next injections. Flow rate differences among the injectors cause differences of fuel quantity from cylinder to cylinder.
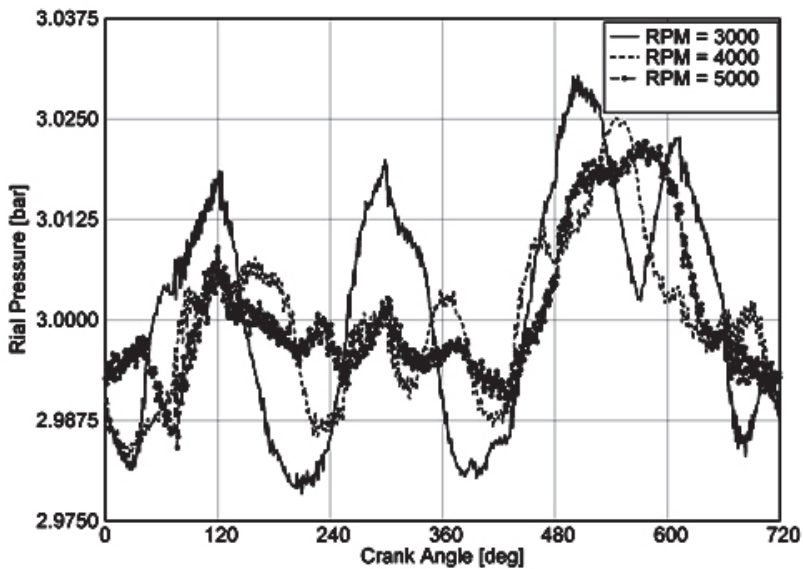

FIGURE 5
Rail Pressure profile for different engine

The speed of sound is an important parameter considered in this study due to the pressure waves propagate along the common rail with velocity, which depends on the speed of sound. For a substance that is not perfect gas, it is desirable to express the speed of sound in terms

of physical property of the substance: the compressibility (John and Keith, 2006). Thus, the sound speed can be calculated using the van der Waals equation, which can be expressed as in Eq. (3):

$$a = \sqrt{\gamma \left(\frac{\partial p}{\partial \rho}\right)_T} \qquad (3)$$

where γ is the specific heat ratio (1.407 for hydrogen at 0^0C) and $(\partial p / \partial \rho)_T$ is the partial derivative of pressure with respect to density for a constant temperature. Finally the speed of sound can be expressed as in Eq. (4) (John and Keith, 2006):

$$a = \sqrt{\gamma \left[\frac{RT}{1-\beta\rho} + \frac{RT\rho\beta}{(1-\beta\rho)^2} - 2\alpha\rho\right]} \qquad (4)$$

where α and β are the constants used in van der Waals's equation of state, T is the absolute temperature, and R is the gas constant which can be expressed as in Eq. (5):

$$R = \frac{universal\ gas\ constant\ (\mathcal{R})}{molar\ mass\ (m)} \qquad (5)$$
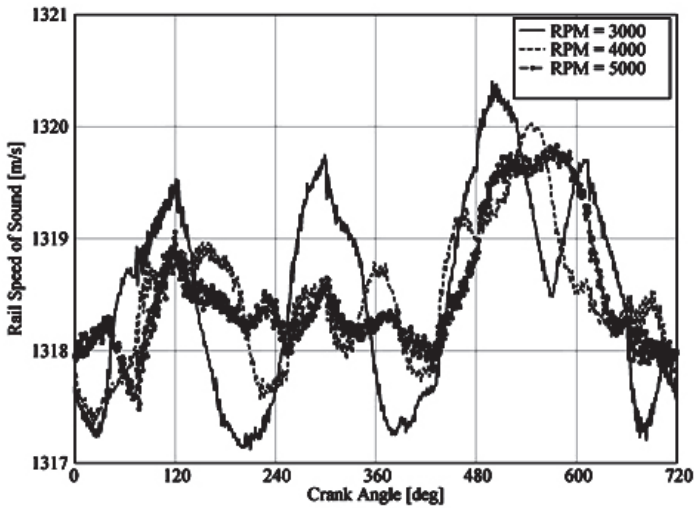

FIGURE 6
Rail speed of sound for different engine

Figure 7 shows the instantaneous hydrogen mass flow rate in the crank angle domain through common rail. The interaction between the speeds curves make distinguishing between them quite difficult. However, higher hydrogen flow rated can be observed at 5000 rpm

engine speed. The rapid closing and opening of the injectors cause high fluctuation in mass flow rate throughout the rail. Reverse flow (negative flow out) can be noticed in some parts of the cycle. The gas dynamic effects distort the common rail and lead to the reverse flow that pressure imbalance occurs between the accumulator (rail) and the pipes of injector. A maximum mass flow of 60 mg/s rate is reported at 5000 rpm; while a minimum value of 29 mg/s (reverse flow) is obtained at 3000 rpm.

Figure 8 shows the variation of injector mass flow rate through the injector orifice with crank angle and speed. It is clearly shown that the influence of the oscillations in rail pressure depends on injection rate. The injected mass flow rate influence the several parameters including the discharge coefficient, orifice diameter, density of the fuel and difference between hydrogen pressure at orifice exit and port pressure. Hence the fluctuations in the injected mass are due to the pressure fluctuations across the injector orifice. The value of the injector hole discharge coefficient is essential for accurate modeling of the injected mass flow rate. A discharge coefficient for injector hole of 0.765 is considered throughout the analysis. Higher mass flow rates can be observed for higher speed. The mass flow rate fluctuations occur in very small amplitudes (maxima of 0.5 mg/s at 5000 rpm; while it is 0.344 mg/s at 3000 rpm with high frequencies.
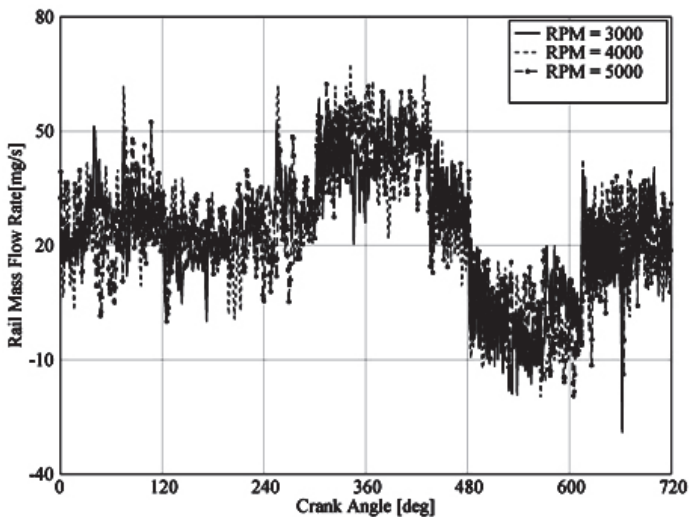

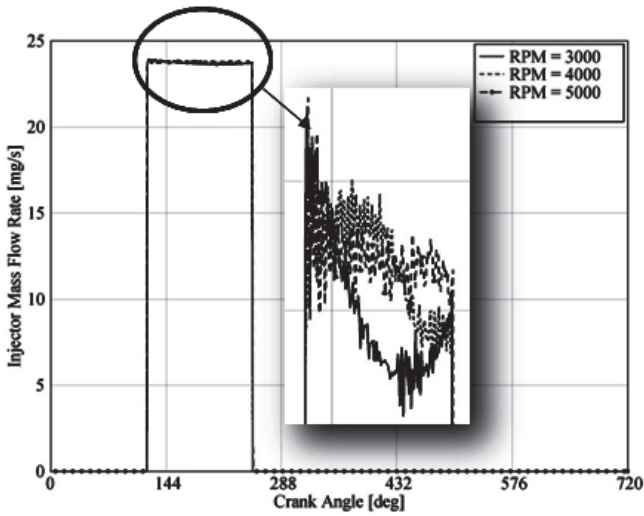
FIGURE 7
Rail Mass Flow Rate for Different Engine

FIGURE 8
Injector Mass Flow Rate for Different Engine

Figure 9 depicts the variation in pressure drop across the injector orifice with crank angle. This is a relevant and flexible factor to improve hydrogen penetration and allows effective mixing during the diffusion burning phase. Again, the pressure fluctuation is present in the behavior of the pressure drop across the injector orifice. The similarity between the two curves (pressure waves and pressure drop) emphasizes that the behavior of the latter is a subsequent to the former. Lower speed 3000 rpm gives higher amplitude and lower frequency. This fluctuation must be damped out as much as possible to avoid supplying the cylinders with different quantities of hydrogen gas. Because, as stated earlier, the injected hydrogen mass depends mainly on pressure difference across the injector orifice. Thus the fluctuation gives variable amounts of hydrogen. The maximum pressure drop of 2.632 bar is obtained at 3000 rpm compared with 2.626 bar at 5000 rpm. As a whole, the pulsation of hydrogen pressure waves has important impact on injection parameters. The effect is related substantially with engine speed. This imposes the engine speed parameter take into account for any tuning process for common rail injection system. The effect of engine speed variation seems to be unimportant for some studied parameters. This may belongs to the interaction with variation of other parameters like the changes in hydrogen density, so that the total impact will be small.
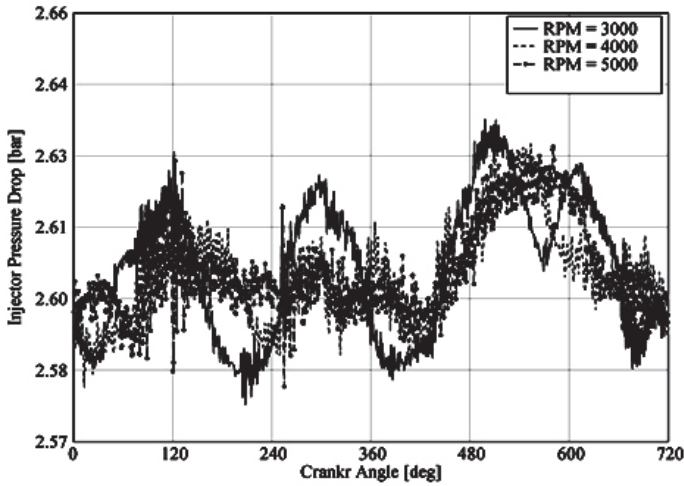
FIGURE 9
Pressure drop across injector for different engine speeds

4.0   CONCLUSIONS

A numerical investigation of single injection system with CR hydrogen fueled engine has been performed. The highly unsteady wave propagation phenomena taking place in the system play a major role in the proper understanding of important injection-system characteristics. From the analysis of system behavior with different operation and geometrical parameters, the following conclusions are drawn:

i.   The proposed common rail injection system for hydrogen engine can play dramatic role in developing port injection hydrogen engine; exactly similar to the extraordinary success for the CR injection system in diesel engine. The CR system is responsible for the ever-increasing share ($\cong$ 40%) of diesel engines in automotive market.

ii.   Although low pressures (2-4 bars) have been investigated for the port injection system, the gas dynamic and pressure propagation phenomena for hydrogen gas fuel is still effective and has major effect in the performance of the CR injection system.

iii.   Hydrogen gas fuel CR injection system is considerably simpler than standard diesel fuel injection system. This is because the fuel is stored at high pressures in a cylinder fuel tank and no need for high pressure pump. However,

the high sound velocity for hydrogen fuel leads to higher propagation speed pressure oscillations.

5.0   ACKNOWLEDGMENT

6.0   REFERENCES

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