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EFFECT OF INTAKE CONDITIONS ON HEAT TRANSFER CHARACTERISTICS FOR THE HYDROGEN FUELED ENGINE

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ABSTRACT

In this work, effect of the inlet conditions for the intake charge on the in-cylinder heat transfer characteristics for port injection Hydrogen Fueled Engine H2ICE are investigated through steady state simulation. One-dimensional gas dynamics was used to describe the flow and heat transfer in the components of the engine model. Firstly a brief demonstration for the model description was inserted; followed by the model governing equations. The engine model is simulated with variable engine speed and AFR with influence of the variation of intake charge conditions (pressure and temperature). Engine speed varied from 2000 rpm to 5000 rpm with increments equal to 1000 rpm, while AFR changed from stoichiometric to lean limit. The inlet pressure is varied from 0.95 bar to 1.05 bar with 0.05 interval and the inlet temperature varied from 290 to 310 with 10 interval. The combined effects for the intake charge conditions with variation of AFR and the engine speed on the in-cylinder heat transfer characteristics for port injection H2ICE are presented in this paper. The baseline engine model is verified with existing previous published result. The results show that the heat transfer characteristics to be more affected by changes in the intake pressure than in the temperature. It is also found that the effect of change for the intake charge pressure disappeared for lean mixture. Beside that the acquired results are presented by examining the dependency of in-cylinder heat transfer rate on the engine speed and AFR.

Keywords: *heat transfer, hydrogen fueled engine, intake conditions, port injection.*

INTRODUCTION

Asaresultofthedevelopmentsinthemodernera,wherenewtechnologiesareintroducedeveryday,transportation'senergyuseincreasesrapidly.Fossilfuelparticularly petroleum fuel is the major contributor to energy production and the primefuelfortransportation.Rapidlydepletingreservesofpetroleumanddecreasingairqualityraisequestionsaboutthefuture.Duetolimitedreservesofcrudeoil,development of alternative fuel engines has attracted more and more concern in theengine community. Theintroduction of alternative fuelsisbeneficialto help alleviatethe fuel shortage and reduce engine exhaust emissions (Huang et al. 2006; Saravanan etal. 2007). One of the alternative energy is hydrogen. Hydrogen, as alternative fuel, hasuniquepropertiesofsignificantadvantageoverothertypesoffuel.Hydrogencanbeused as a clean alternative to petroleum fuels and its use as a vehicle fuel is promising inthe effects to establish environmentally friendly mobility systems. Extensive studieswere investigated on hydrogen fueled internal combustion engines (Kahraman, et al.2007; Rahman et al. 2009; Stockhausen et al. 2000). With increasing concern about theenergyshortageandenvironmentalprotection,researchonimprovingenginefueleconomy,hydrogenfueledengineisbeingdevelopedintoahydrogenfueledenginewith different type of fuel supply method (Eichlseder, et al. 2003; Kim, et al. 2005;Ganesh,,et al.2008).

It is well known that the performance of an engine is influenced by the intakechargeconditions.Themostimportantintakeconditionsaffectinggasengineperformance are the intake pressure and temperature (Soaresand Sodre,2002; Sodreand Soares, 2003). But the effect of the conditions for the intake charge on the in-cylinder heat transfer is not well recognized. The aim of the research work presented inthis paper is to assess the potential of inlet charge conditions (temperature and pressure)forin-cylinderheat transferreduction ofport injection H_2ICE. (Vasanthy and Jeganathan 2007, Vasanthy et.al., 2008, Raajasubramanian et.al., 2011, Jeganathan et.al., 2012, 2014, Sridhar et.al., 2012, Gunaselvi et.al., 2014, Premalatha et.al., 2015, Seshadri et.al., 2015, Shakila et.al., 2015, Ashok et.al., 2016, Satheesh Kumar et.al., 2016).

MATERIALSANDMETHODS

A single cylinder port injection hydrogen fuel model was developed utilizing the GT-suite software. The injection of hydrogen was studied in the midway of the intake port.The computational model of single cylinder hydrogen fueled engine is shown in Fig. 1.The engine specifications used to make the model (A) are listed in Table 1. The intakeandexhaustportsoftheenginecylinderaremodeledgeometricallywithpipesandtheair enters through a bell-mouth orifice to the pipe. The discharge coefficients of the bell-mouth orifice were set to 1 to ensure smooth transition. The intake runners were linkedtotheintakeportswith0.04mdiameterand0.08mlength.Thetemperatureofthepistonishighertha nthecylinderheadandcylinderblockwalltemperature.Heattransfer multiplier is used to take into account for bends, additional surface area andturbulencecausedbythevalveandstem.Thepressurelossesareincludedinthedischarge coefficients calculated for the valves but no additional pressure losses wereused for wall roughness. The exhaust port was modeled as rounded pipe with 0.04 minlet diameter and 0.8 m length. Exhaust wall temperature was calculated using a modelembodiedin each pipe.

A simulation of the wall heat transfer is an imperative condition for the accurateanalysis of the working process of ICE. The engine model is adopting the Woschni'scorrelation (Woschni, 1967) for the in-cylinder heat transfer calculation. The originalvalues of the constant in the correlation were multiplied by factor equal to 1.8, resultingin a better match with the experimental data (Aceves and Smith, 1997). The authorsfound during the analysis that the heat transfer correlation under predicts heat transferloss. (Manikandan et.al., 2016, Sethuraman et.al., 2016, Senthil Thambi et.al., 2016, Ashok et.al., 2018, Senthilkumar et.al., 2018,).

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Table 1: Engine specifications for model A.

Parameter	Value	Unit
Bore	100	mm
Stroke	100	mm
Connecting rod length	220	mm
Compression ratio	9.5	-
Inlet valve open	9	CA(BTDC)
Exhaust valve open	55	CA(BBDC)
Inlet valve close	84	CA(ABDC)
Exhaust valve close	38	CA(ATDC)
No. of cylinder	1	-

No. of cylinder 1 -

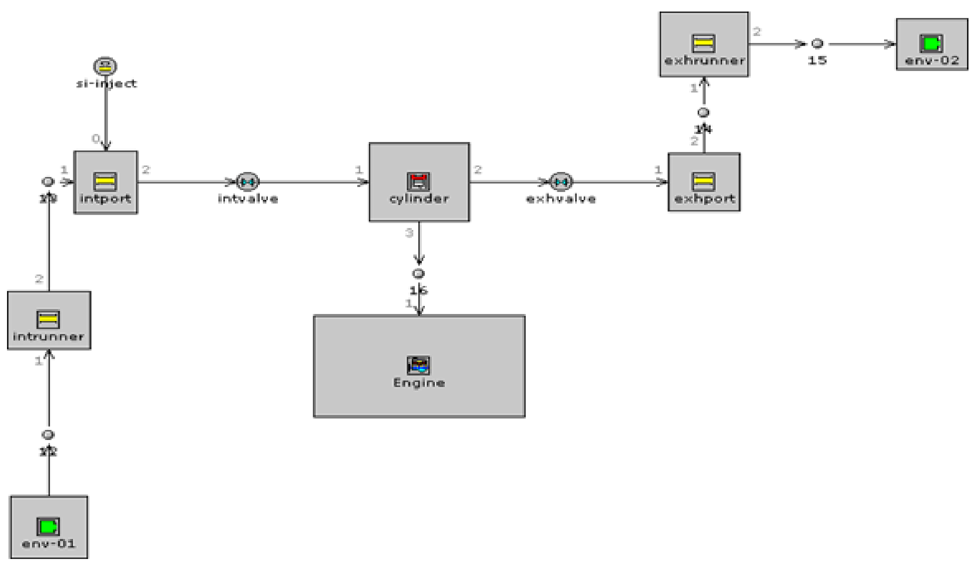

Figure 1: Model of single cylinder four stroke,port injection hydrogen fueled engine

HeatTransferModelingEquations

One-dimensional gas dynamics model is used to represent the flow and heat transfer inthe components of the engine model. Engine performance can be studied by analyzingthe mass, momentum and energy flows between individual engine components and theheatandworktransferswithineachcomponent.Tocompletethesimulationmodel,otheradditionalformulasbesideofthemaingoverningequationsareusedforcalculationsofthepressurelosscoefficient, friction coefficient,andheattransfer.

Thepressurelosscoefficientisdefinedby:

$$C_{pl} = \frac{p_1 - p_2}{\frac{1}{2}\rho u_1^2} \tag{1}$$

where$p_1$and$p_2$aretheinletandoutletpressurerespectively,ρchargedensityand$u_1$theinletvelocity. Thefrictioncoefficientcanbeexpressedforsmoothandroughwallsas Equation(2)and (3)respectively:

whereRe_D,$D$and$z$areReynoldsnumber,pipediameterandroughnessheightrespectively.

$$C_f = \frac{16}{Re_D} \qquad Re_D < 2000;\ Re_D = \frac{vD}{\nu}$$
$$C_f = \frac{0.08}{Re_D^{0.25}} \qquad Re_D > 4000 \tag{2}$$

Theamountofheatratewhichistransferredfromthein-cylinderhotgasestoitswalls calculatesaccordingto theformulaofNewton's lawofcooling:

$$Q = hA(T_g - T_w) \tag{4}$$

where$Q$, A, $T_g$and $T_w$are amount of heat transfer, heat transfer area, gas temperatureandwall temperaturerespectively.

Theheattransfercoefficientdependsoncharacteristiclength,transportproperties, pressure, temperature and characteristic velocity. There is a wealth of heattransfercorrelationsfordescribing heattransfer processinsidecombustionchambersuch as Eichelberg's equation (Eichelberg 1939), Woschni's equation (Woschni 1967)and Annand's equation (Annand 1963). The in-cylinder heat transfer is calculated by aformula which closely emulates the classical Woschni correlation. A unique feature ofWoschni correlation is the gas velocity term while most of the other correlations use atimeaveragedgasvelocityproportionaltothemeanpistonspeed,Woschniseparatedthe gas velocity into two parts: the unfired gas velocity that is proportional to the meanpiston speed, and the time-dependent, combustion induced gas velocity that is a functionofthedifferencebetweenthemotoringandfiringpressures.Theheattransfercoefficientcan beexpressed as Equation (5):

$$h = 3.26 D^{-0.2} P^{0.8} T_g^{-0.55} w^{0.8}$$
$$w = 2.28 C_m + 0.00324 \frac{(P - P_m) V_h T_r}{P_r V_r} \quad (5)$$

where D, P, P_m, T_g, V, C_m, $V_h$and r are the bore diameter, pressure, motored pressure,gas temperature, volume, mean piston speed, swept volume and a reference crank anglerespectively.

Thisapproachkeepsthevelocityconstantduringtheunfiredperiodofthecycle
and then imposes a steep velocity rise once combustion pressure departs from motoringpressure. This empirical equation was derived for hydrocarbon combustion engines andit was based on observations using the turbulent heat transfer equation for tubes. Arealistic simulation of the wall heat transfer is an imperative condition for the accurateanalysis of the working process of ICE. So, for the hydrogen fuel engines should becorrect choice for the formula which gives the best guess for the amount of heat transferfrom the combustion chamber gas to its walls. The engine model for (Aceves and Smith1997) estimate engine heat transfer by using Woschni's correlation (Woschni 1967). Itwas found during the analysisthat the heat transfer correlation under predicts

heattransfer loss. Therefore, for the present model the original values of the constant in thecorrelation were multiplied by factor equal to 1.8, resulting in a better match with theexperimental dataaccordingto (AcevesandSmith1997).

RESULTSANDDISCUSSION

Steady state gas flow and heat transfer simulations for the in-cylinder of four stroke portinjection spark ignition hydrogen fueled engine model is running for two operationparametersnamelyAir-FuelRatio(AFR)andenginespeedwithinfluenceofthevariation of inlet conditions (pressure and temperature). The Air-Fuel Ratio (AFR) wasvariedfrom stoichiometriclimit(AFR =34.33:1based on mass)toverylean limit(AFR
=171.65) and engine speed was varied 2000-5000 rpm with 1000 rpm interval. As wellas the inlet pressure varied from 0.95 bar to 1.05 bar with 0.05 interval and the inlettemperaturevariedfrom290 to 310with 10 interval

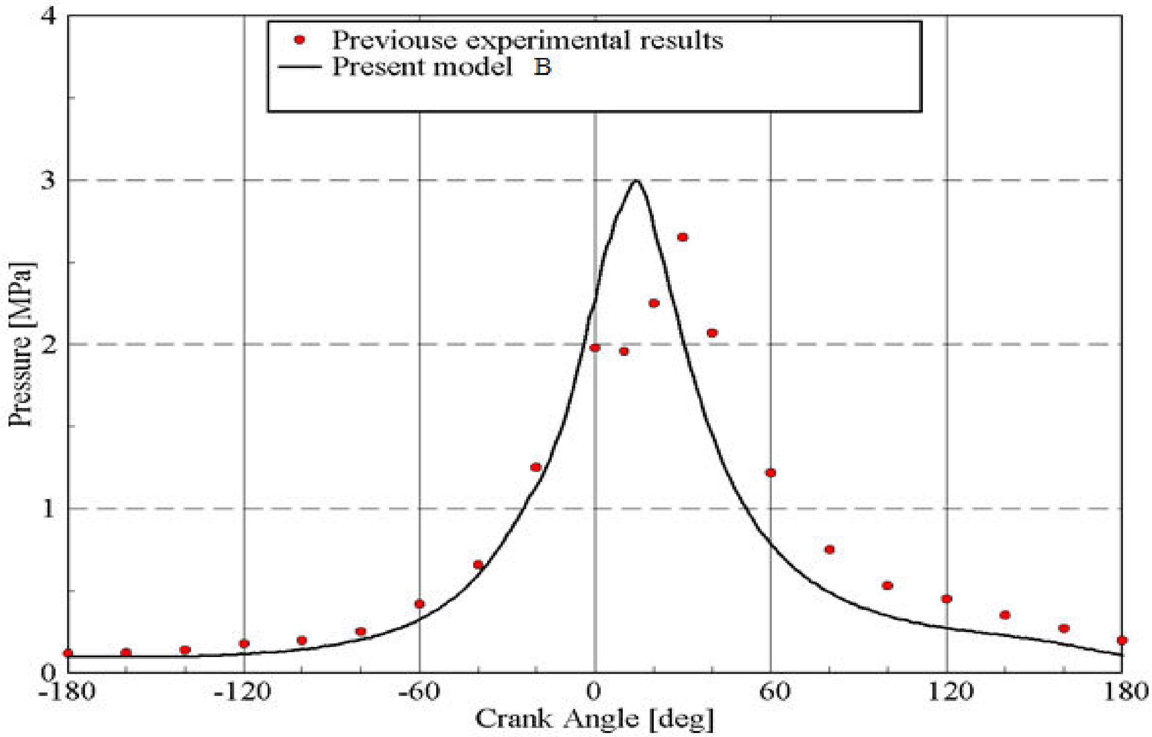

Figure 2: Comparison between published experimental results Lee *et al.* (1995) andpresentsinglecylinderport injectionenginemodelbased onin-

cylinderpressuretraces.

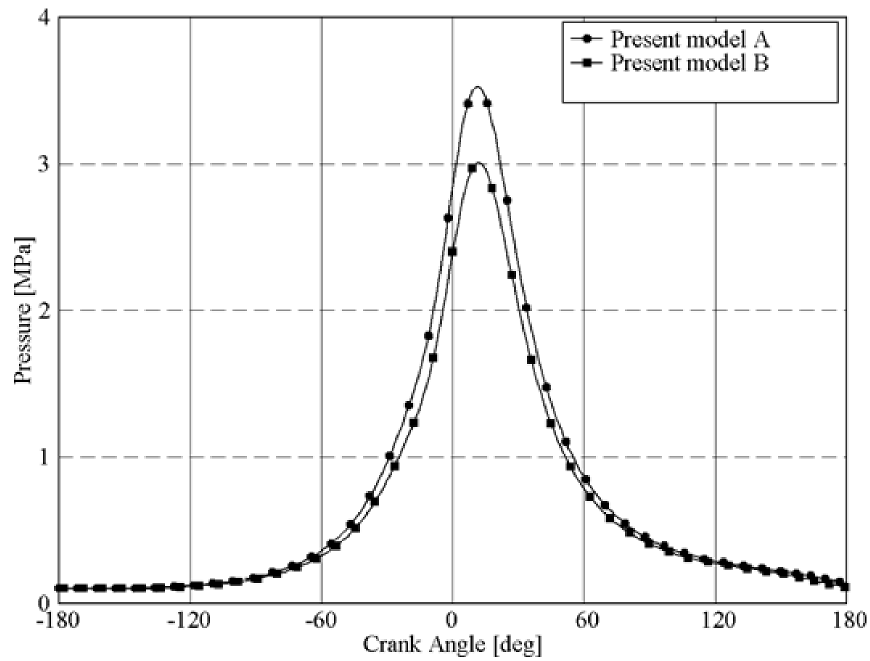

Figure 3: Comparison between models (A and B) based on in-cylinder pressure traces.

Effect ofIntakeChargePressureontheHeat TransferRate

Effect of the inlet pressure on the in-cylinder heat transfer rate at different engine speedis shown in Figure 4. It can be seen that the in-cylinder heat transfer rate increases withincreases of inlet pressure for the intake charge for all engine speed. At high enginespeed the effects of pressure for the intake charge are morepronounced, where theincrementinheattransferrateisincreasingwithincreaseoftheenginespeedforallinlet pressure values.Figure 5 shows the effect of intake charge pressure variation onthe in-cylinder heat transfer rate with different AFR values. As intake charge pressureincrease the in-cylinder heat transfer increases for all AFR values. However, it alsoshoweddecreaseinincrement trend bymovingfrom thestoichiometricto leanlimits.

Itcanbeseenthattheheattransferratehasincreasedwithincreasingenginespeeddue toincreasing thedrivingforce(forcedconvection)fortheheattransferinsidethecylinder.While decreasedby increasingAFRbecauseofdecreasingintheenergycontent for the inlet charge to the cylinder. The observation of the heat transfer ratebehavior through the cylinder to ambient revealed that in case of hydrogen fuel giveshighervalues than thatofhydrocarbonfuelsdue to the higher heating value, fasterflamespeedandsmallquenchingdistance.Thiscanbeusedasanindicatorforclarifyingthatthehydrogenfuelgivesmoreheatlosscomparedtohydrocarbonfuel.

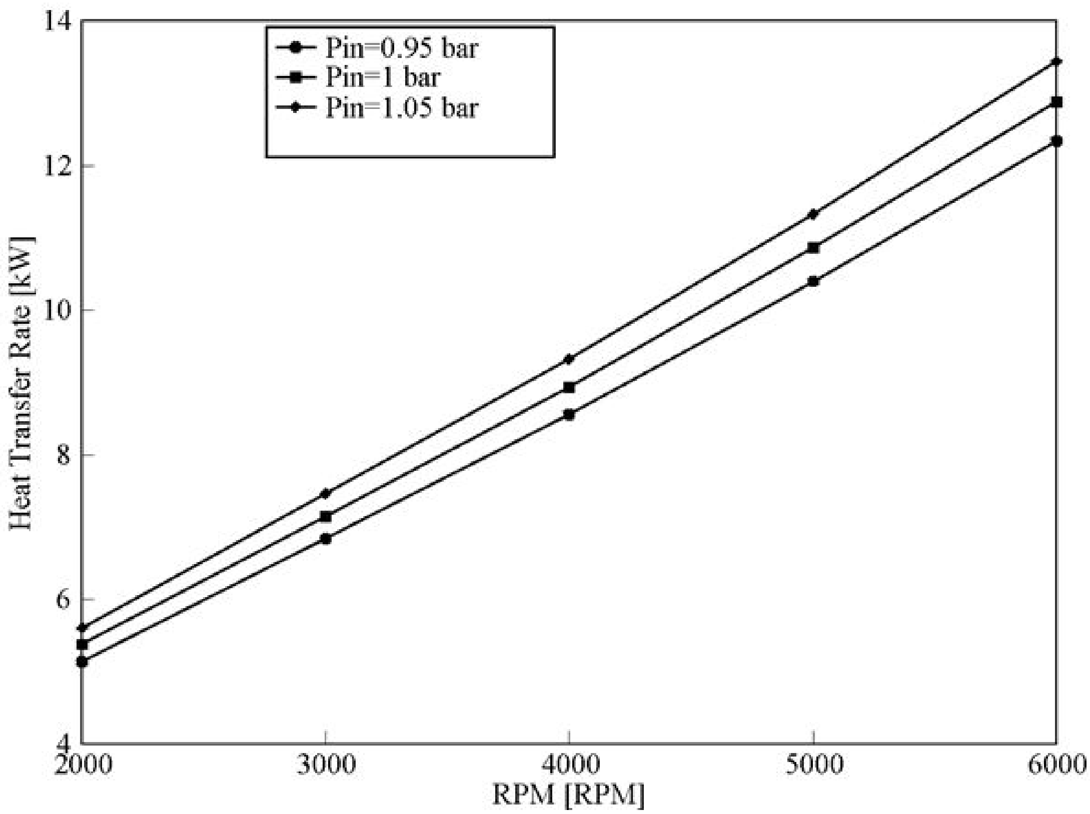

Figure 4: Variation of in-cylinder heat transfer rate with engine speed and variable intake charge pressure.

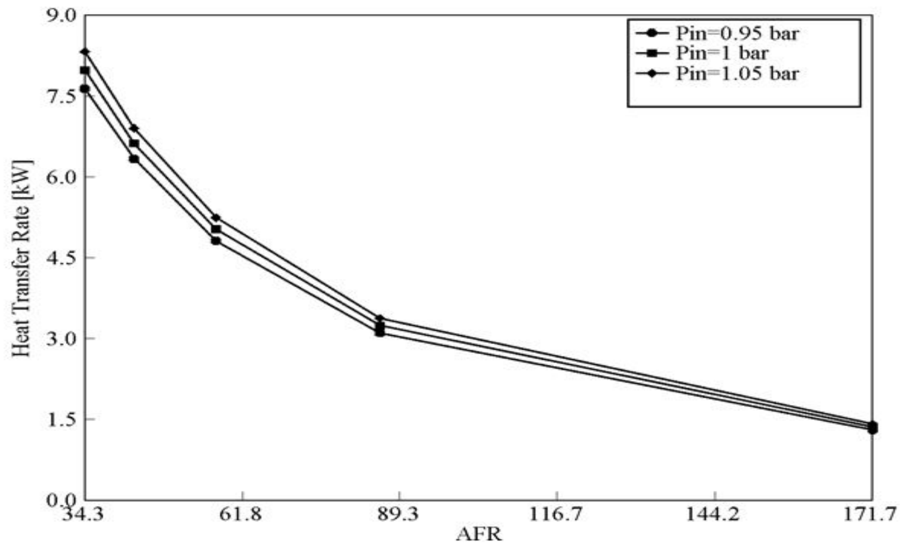

Figure 5: Variation of in-cylinder heat transfer rate with AFR and variable intake charge pressure.

Effect of Intake Charge Temperature on the Heat Transfer Rate

Variation of in-cylinder heat transfer rate with engine speed for different intake charge temperature is revealed in Figure 6. It appeared that negligible effect for the intake charge temperature on the in-cylinder heat transfer rate, especially at lower engine speed values. The combined effect for AFR and intake charge temperature on the in-cylinder heat transfer rate is demonstrated in Figure 7. There is no impact of the intake charge temperature on the behavior of in-cylinder heat transfer rate with AFR variation.

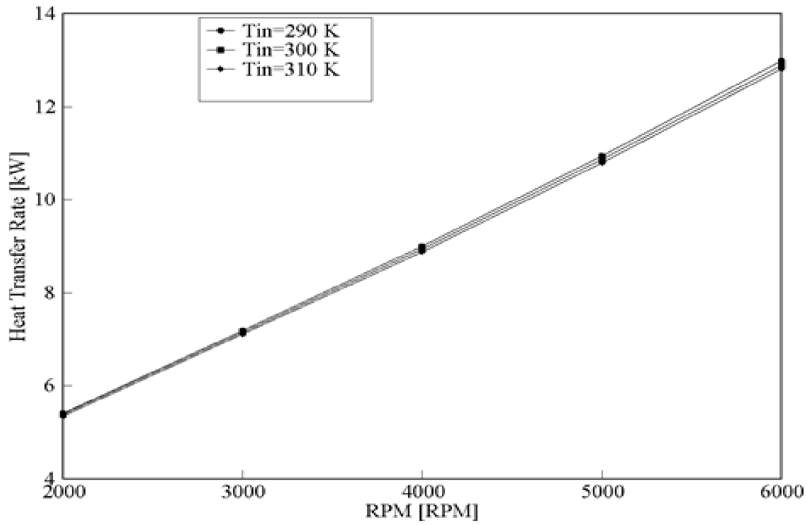

Figure 6: Variation of in-cylinder heat transfer rate with engine speed and variable intake charge temperature.

CONCLUSION

The combined influence of the engine speed and AFR with intake charge conditions(pressureandtemperature)onthein-cylinderheattransfercharacteristicsforportinjection H_2ICE have been investigated and quantified. The results show that increasingthe pressure for intake charge gives negative impact on the in-cylinder heat transfer ratewithenginespeedandAFRvariation.Thereisnoimpactoftheintakechargetemperature on the behavior of in-cylinder heat transfer rate with AFR variation andnegligibleeffectwithenginespeedvariation.Besidethattheacquiredresultsarepresented by examining the dependency of in-cylinder heat transfer rate on the enginespeedand AFR.

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