NUMERICAL AND EXPERIMENTAL INVESTIGATIONS OF EGR DISTRIBUTION IN A DI TURBOCHARGED DIESEL ENGINE

Reza Rahimi[1], S. Jafarmadar[2], Sh. Khalilarya[3], A. Mohebbi[4]
[2,3] Mechanical Engineering Department, University of Urmia, Urmia,,West Azerbaijan, Iran
[4] Mechanics of Farm Machinery Engineering Department, University of Urmia, Iran
[1] Corresponding author: Mechanical Engineering Department, University of Urmia, Urmia,,West Azerbaijan 57561-15311, Iran,
E-mail: reza67_mech@yahoo.com; s.jafarmadar@urmia.ac.ir

Received January 2013, Accepted March 2013
13-CSME-02, E.I.C. Accession 3460

ABSTRACT

This paper presents the results of numerical and experimental investigations to evaluate the distribution of exhaust gas recirculation (EGR) between cylinders in a DI turbocharged diesel engine. The turbulent three-dimensional flow field was analyzed by the numerical solution of conservation equations with an appropriate turbulence model. EGR was applied to intake manifold with various rates at cooled and non-cooled states. The experiments were conducted on an MT4.244 turbocharged DI diesel engine under full load condition at 1900rpm. The model was validated by experimental data with a good agreement between experimental measurements and numerical predictions. Using this method, it is possible to control EGR distribution so as to reduce emissions formation as well as to improve performance.

Keywords: three dimensional models; intake manifold; turbocharged DI diesel engine; cooled and non-cooled EGR; EGR distribution.

ENQUÊTES NUMÉRIQUE ET EXPÉRIMENTALE DE DISTRIBUTION DU GER DANS UN MOTEUR DIESEL TURBOCOMPRESSÉ À INJECTION DIRECTE

RÉSUMÉ

Cet article présente les résultats des enquêtes numérique et expérimentale pour évaluer la distribution du Gaz d'Echappement Recyclé (GER) entre les cylindres d'un moteur diesel turbocompressé à injection directe. Le champ d'écoulement tridimensionnel turbulent a été analysé par la résolution numérique des équations de conservation avec un modèle de turbulence approprié. GER a été appliqué au collecteur d'admission avec des taux différents aux états refroidis et non refroidis. Les essais ont été réalisés sur un moteur diesel turbocompressé MT4.244 à injection directe dans des conditions de pleine charge à 1900 T/MN. Le modèle a été validé par des données expérimentales avec un bon accord entre les mesures expérimentales et les prévisions numériques. En utilisant cette méthode, il sera possible de-contrôler la distribution du GER afin de réduire les émissions polluantes et d'améliorer les performances.

Mots-clés: modèles tridimensionnels; collecteur d'admission; moteur diesel turbocompressé à injection direct; GER refroidi et non refroidi; distribution du GER.

NOMENCLATURE

EGR	exhaust gas recirculation
DI	direct injection
CFD	computational fluid dynamics
L	Litters
° CA	degrees of crank angle
BTDC	before top dead center
Γ_{ϕ}	fusion coefficient (kg/m s)
S_{ϕ}	source term
$\vec{u}$	locity vector (m/s)
ρ	density (kg/m^3)
ε	rbulent dissipation rate (per unit mass) (m^2/s^3)
rpm	revaluation per minute
ϕ.	neralized variable
LCV	light commercial vehicle
Rpm	revolutions per minute
NO_X	nitrogen oxides
NO	nitric oxide
CO_2	carbon dioxide
PM	Particulate Matter

1 INTRODUCTION

DI diesel engines are the main power unit for heavy duty vehicles because of high thermal efficiencies, resulting from their high compression ratio and fuel lean operation. Extra oxygen in the cylinders is needed to facilitate complete combustion and also to compensate non-homogeneity of fuel distribution in cylinder. However, high flame temperatures are predominating because of formation of locally stoichiometric air–fuel ratio zones in such heterogeneous combustion processes [1]. Consequently, Diesel engine combustion generates large amounts of NOx emission because of these high flame temperature zones in the cylinder [1, 2]. Exhaust gas recirculation into the intake manifold is a very effective method for reducing combustion temperatures and NOx emissions in conventional diesel engines. Attempting to decrease NOx emissions by applied EGR involves a complex phenomenon which might even increase NO_X production [3].

Over the years, various experimental and numerical reports regarding the use of EGR in internal combustion engines have been published. The results of these studies are presented in detail as follows: Hentscheland et al [4] investigated the formation of soot in a 1.9 L DI diesel engine under various EGR rates and found that with increasing EGR rates, the amount of soot formed slightly increases, but the amount of soot oxidized during combustion decrease significantly. Ladommatos et al [5] conducted a detailed study about the effects of EGR on formation of emissions formation in a 2.5 L, four-cylinder DI diesel engine. Their results showed that the reduction in NOx emission and the increase in particulate emission due to EGR could mainly be attributed to the dilution of charge. Cherian et al [6] showed that the distributions of fuel and oxygen mass in a larger mass in the premixed-burn region for higher EGR conditions and implying higher potential for heat release during the premixed burn. According to the experimental result of this study, an increasing ignition delay by increasing EGR does not decrease the equivalence ratio that would be required for reducing soot formation. The research of Hountalas et al [7] showed that no compromise should be made between NO_X emissions and engine efficiency while using cooled EGR. Furthermore, cooled EGR is necessary to prevent soot emissions from rising to unacceptable levels. The need for EGR cooling is more evident at high EGR rates and low engine speeds. From the theoretical investigation it has been revealed that a different effect of EGR temperature is to be expected at part load operation. Saleh [8] carried out an experimental investigation about the effect of exhaust gas recirculation on exhaust emissions and performance in a diesel engine operating with jojoba methyl ester, and concluded that the using an EGR cooler at full load has a positive effect on improving the engine economy and decreasing the exhaust emissions. Mobasheri et al [9] carried out a numerical analysis in order to explore the combined effects of split injection strategies and EGR on engine performance and emission formation in a heavy duty DI-diesel engine. The results show that although EGR has a positive effect on NOx reduction by lowering peak cylinder temperatures, but there is a substantial trade-off in increased soot emissions due to increased high temperature in rich regions. Moreover, they showed that the amount of soot formed in these regions is reduces considerably by use of multiple injections. Multiple injection schemes improve fuel–air mixing and lean out the in-cylinder mixture, thus reducing the high soot forming regions. The result of the work by Millo et al [10] showed that the use of a long route EGR system results in lower NOx emissions. Maiboom et al [11] carried out an experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine and concluded that increase of inlet temperature at constant EGR rate sometimes gives an increased NO_X emission, rather than a decrease, with increased inlet temperature. As a consequence, the increase of inlet temperature generated by EGR can be either positive or negative depending on operating conditions, indicating that attention should be paid during engine designing and calibration. Maiboom et al [12] experimentally studied the influence of cylinder-to-cylinder variations in EGR distribution on the resulting NOx–PM trade-off at various EGR rate in an automotive high-speed direct injection diesel engine and showed that unequal EGR distribution results in increased NOx and PM emissions compared too well-mixed air and EGR gases. Furthermore, the increase in emissions is due to cylinder-to-cylinder variations in both gas composition and intake temperature. Karthikeyan et al [13] attempted to evaluate homogeneous mixing of Exhaust Gas Recirculation (EGR) with air in a LCV (Light Commercial Vehicle) diesel engine with asymmetric manifold by application numerical and experimental techniques. They concluded that at low EGR pressures, mixing of exhaust gas with air will be better for all EGR operating conditions.

As can be seen in the relevant literature, has been no numerical or experimental study of EGR distribution in turbocharged DI diesel intakes. In this work a CFD code has been used to predict EGR distribution between cylinders in both cooled and hot cases and at various rates.

2 EXPERIMENTAL SET-UP AND PROCEDURE

The experimental tests were carried out on a semi-heavy duty Motorsazan MT4.244 agricultural engine. This is a 3.99 L turbocharged DI diesel engine. The main specifications of the engine are given in Table 1. Fig. 1 shows schematic diagram of experimental set-up. Table 2 shows measurement accuracy of instruments involved in the experiment for various parameters.

Specifications of test engine. .Table 1

Type	Turbocharged
Maximum power	61kW@2000rpm
Maximum torque	3600N.m@1300rpm
Bore × stroke	100 × 127 mm
Compression ratio	17.5:1
Number of cylinders	4
Number of valves per cylinder	2
Combustion chamber type	Bowl-in-piston
Injection system	Pump-line-nozzle
Number of injection holes	4
Opening pressure of nuzzles	250 bars
Fuel	Diesel

Measurement accuracy. .Table 2

NO_X (AVL DiCom4000)	1ppm
Smoke (AVL 415S smoke meter)	0.1
CO (AVL Digas4000)	0.01%
Inlet & exhaust CO_2 (AVL Digas4000 Light)	0.01%
In-cylinder pressure (AVL GU13G)	<1%

As shown in this figure, an AVL DiCom4000 gas analyzer was used to measure CO_2 in the exhaust manifold and another was used to measure CO_2 concentrations in the cross-section of 1 and 2 cylinder intake ports in order to calculate EGR rate. Since this analyzer could not measure CO_2 of high positive pressure gases a surge tank was used to reduce pressure of inlet gas into analyzer. The accuracy of inlet and exhaust CO_2 measurements was 0.01% (by volume). To control EGR rate manually an EGR control valve was provided. To lower the temperature of the recycled exhaust gases, a cross-counter-flow shell and tube heat exchanger (EGR cooler) containing 60 tubes was designed and then was installed in the EGR loop. The hot exhaust gases were passed tube side, while cool city water passed shell side. EGR valve and the section of duct from the engine exhaust to heat exchanger were also made resistant to exhaust temperatures that are commonly in a range of 100-600 °C.

In the present study, the percentage of exhaust gas recirculation was defined by ratio of the CO_2 concentration in the intake of the engine to CO_2 concentration in the exhaust as follows:

$$\text{EGR ratio} = \frac{\text{Intake CO2 concentration}}{\text{Exhaust CO2 concentration}} * 100 \quad (1)$$

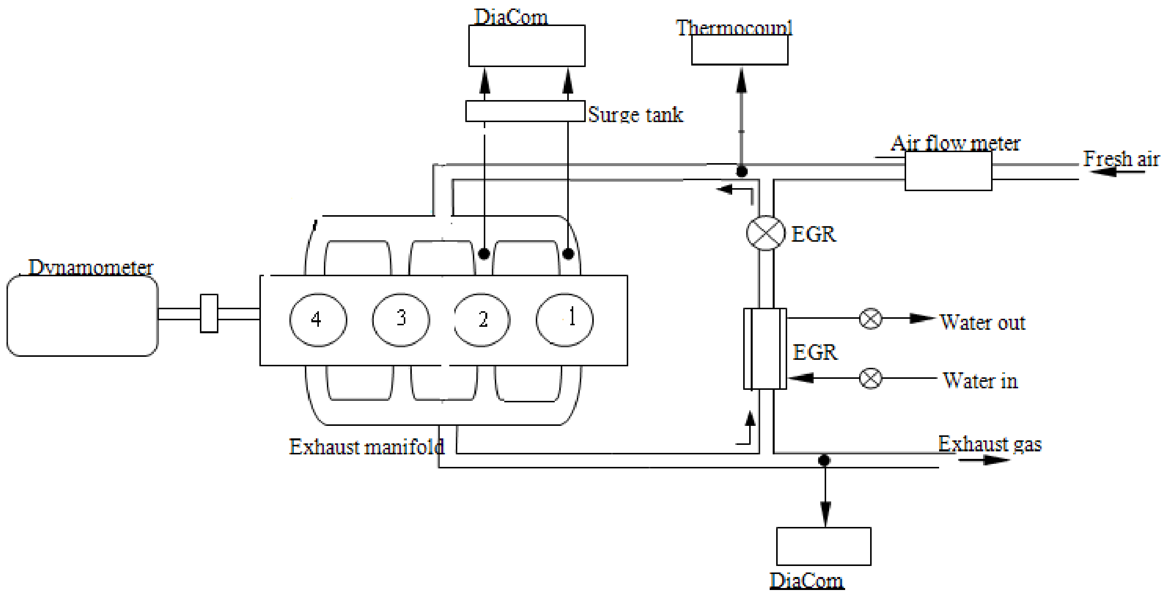

Fig. 1. Schematic diagram of experimental set-up.

As shown in Fig.1, in order to study EGR distribution between cylinders, CO_2 measurements was carried out in the intake manifold before the intake valve of cylinders 1 and 2. Due to symmetrical configuration of intake manifold, it seems that CO_2 concentrations in inlet ports 3 and 4 are similar to 1 and 2. The operating conditions of engine in all the experiments are at rated speed of 1900 rpm (maximum power engine speed) and full load. These experiments were carried out at injection timing; 5° CA BTDC as base (conventional) injection timing and 12° CA BTDC as advanced injection timing, with hot and cooled EGR and various EGR rates from 0 up to 10%. EGR temperatures were maintained at 460-480 °C and 100-120 °C for hot and cooled EGR, respectively.

3 MODEL FORMULATION

The concentration of CO_2 emissions and EGR distribution proportion was calculated by Computational Fluid Dynamics (CFD) with appropriate boundary conditions. The geometry of inlet manifold used for modeling and solving the governing equations is shown in Fig. 2. A grid independence study was carried out for the model and the mesh with 0.7 million tetrahedral cells was found to be adequate for capturing the results accurately.

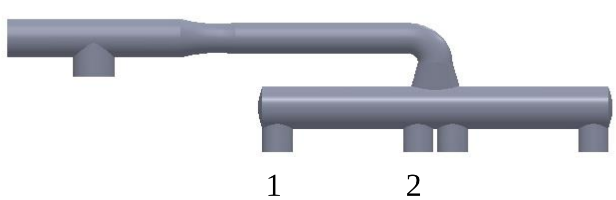

Fig. 2. The intake system consists of air duct, EGR and intake manifold.

Flow through an intake manifold is dependent on the timing or crank angle positions. Unsteady state simulation can predict how an intake manifold works under real conditions. The boundary conditions are no longer constant but vary with time. These boundary conditions are obtained from experimental work. The intake system consists of air duct, EGR and intake manifold (as shown in Fig. 2). The CFD code used a RNG k-ε turbulence model [14] with a few modifications was used to introduce the compressibility of fluid in universal coordinates for turbulence modeling. Furthermore, transport equations for the conservation of momentum, species and energy were used in present study, as suggested in Ref [15].

Transport equations for the RNG k-ε model are as follows:

$$\frac{\partial(\rho\phi)}{\partial t} + \nabla.(\rho\vec{u}\,\phi) = \nabla.(\Gamma_{\phi}\nabla(\phi)) - \rho\varepsilon + S\phi + G\phi \tag{2}$$

Where Γ_{ϕ} and S_{ϕ} are the diffusion coefficient and source term, G_{ϕ} represents the generation of turbulence kinetic energy due to the mean velocity gradients [16]. Furthermore, the source terms of the turbulent kinetic energy and its dissipation are the same as in Ref [17]. For the simulation of two fluids namely air and exhaust gas, various quantities of 2%, 5%, 7.5%, 10.5%, 13.5% (by concentration) were used. The values of EGR components were measured by experimental test. Following boundary conditions were used for the CFD analysis:

1. Air inlet condition: Compressor temperature and outlet pressure were taken from the engine test data.
2. EGR inlet condition: Exhaust manifold pressure was measured before the exhaust gas entrance into the air duct.
3. Outlet condition: The average pressure in the respective cylinder during the intake a stroke.

4 RESULTS AND DISCUSSION

The aim of this section is to numerically investigate EGR distribution between cylinders under various EGR rates and at two hot and cooled states. The numerical data results were compared with corresponding experimental data measurements. As shown in Fig. 3, the numerical data results are in good agreement with experimental data. Furthermore, Fig. 3 shows CO_2 concentration (EGR rates) in hot and cooled EGR in two cylinders. According to experimental and numerical data at lower percentage of EGR, CO_2 concentration is the same in both, but with increasing EGR percentage, CO_2 concentration differs.

Fig. 4 shows the air flow and EGR into the manifold is of almost uniform distribution at cooled EGR. It is possible that at hot EGR case because of the almost similar inertia force for air and exhaust gas and incomplete mixing, EGR distribute unevenly to the engine cylinders resulting in cylinder-to cylinder variation. Also the experimental data confirm this behavior.

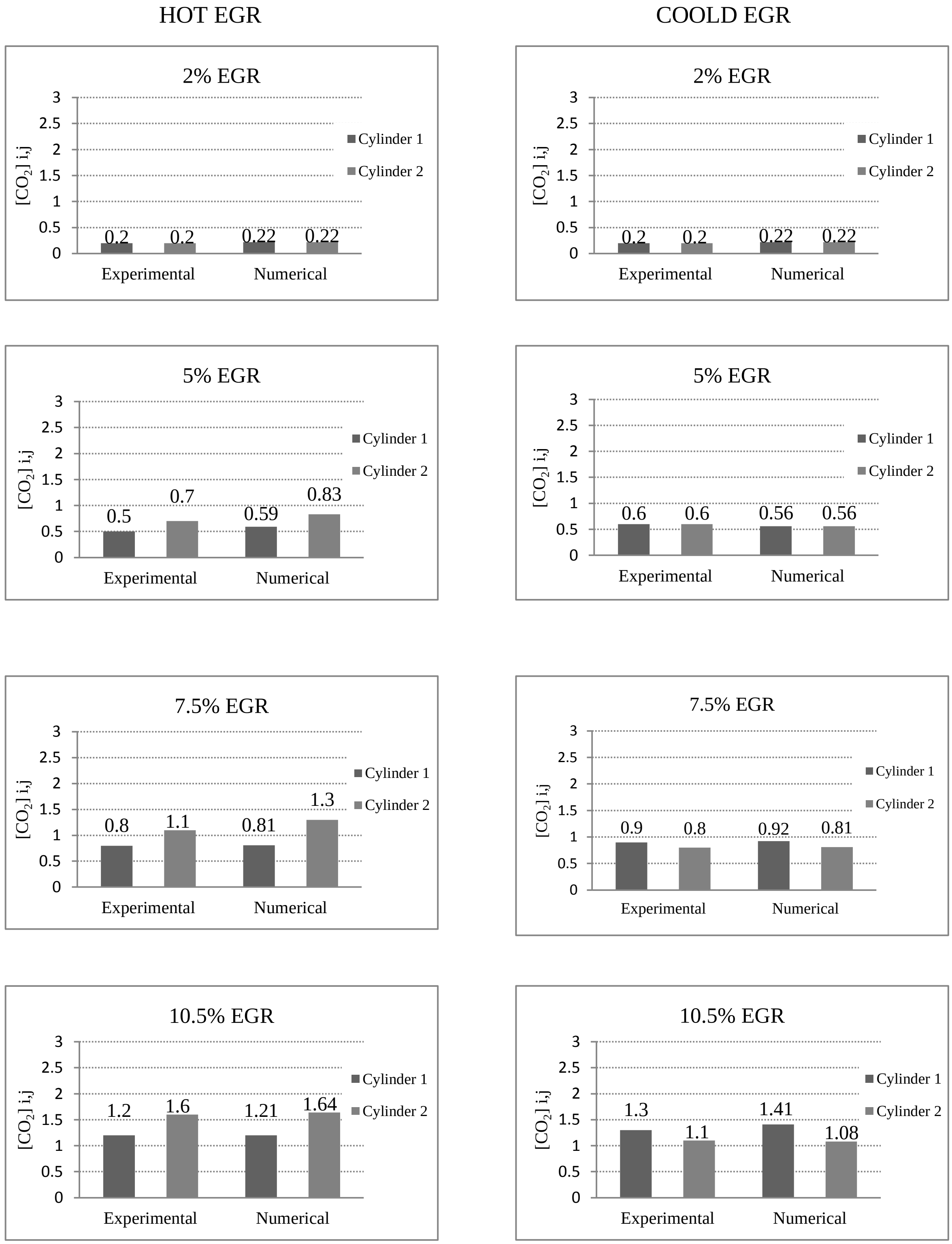

Fig. 3. CO_2 concentration at each inlet ports of cylinder 1 and 2 in cases of hot and cooled EGR for various EGR rates (continues).

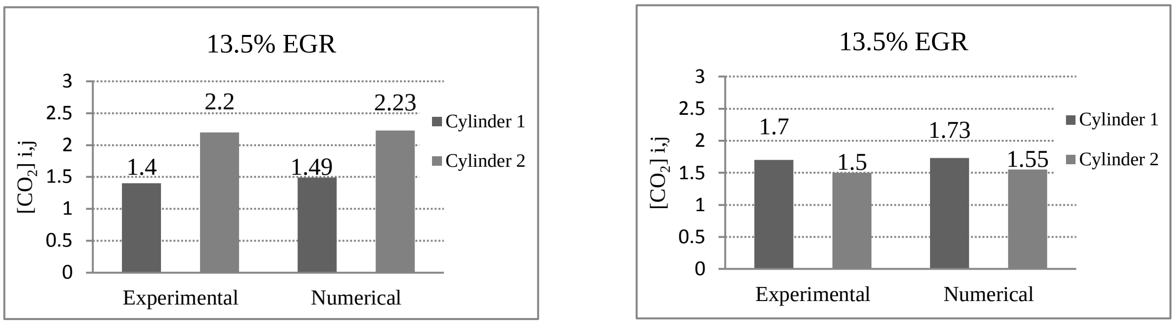

Fig. 3. CO_2 concentration at each inlet ports of cylinder 1 and 2 in cases of hot and cooled EGR for various EGR rates (continued).

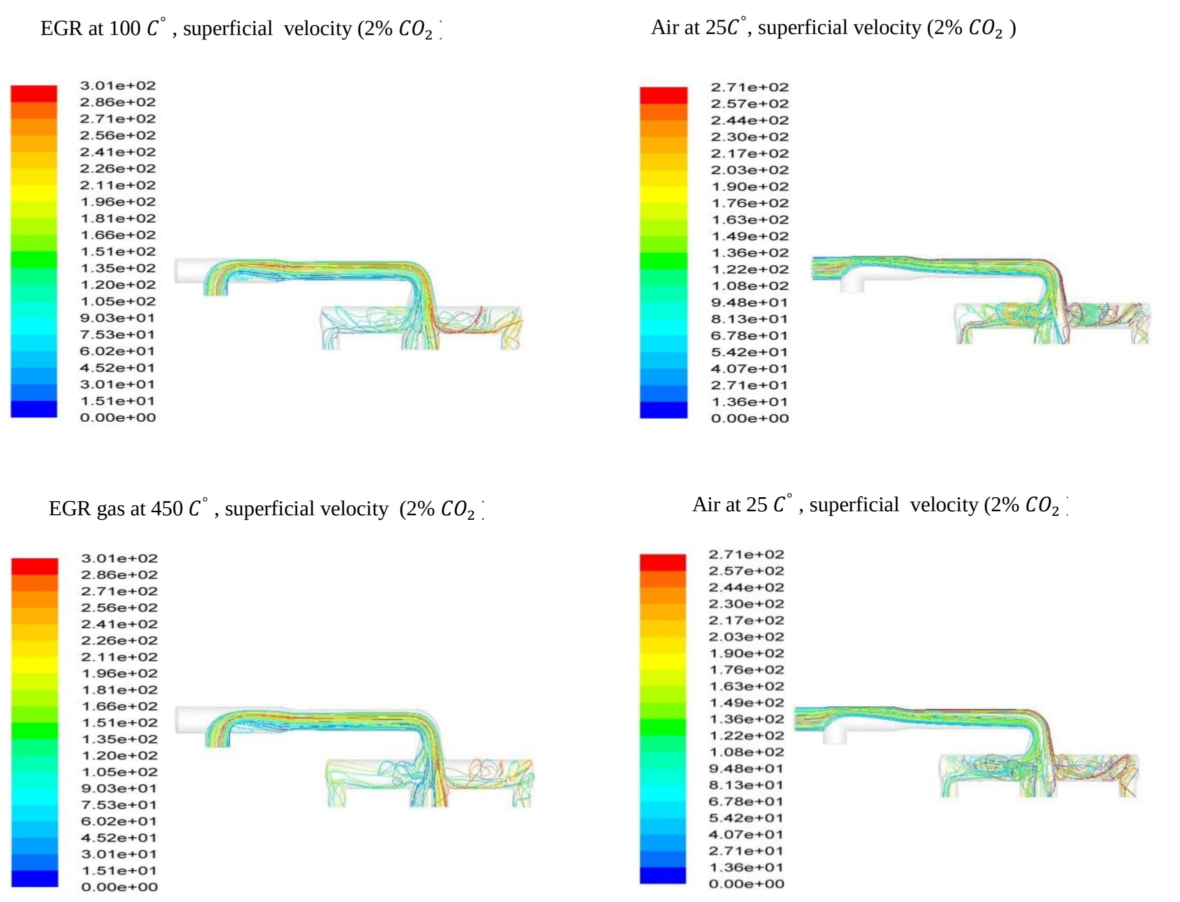

Fig. 4. Stream line and volume fraction of air and EGR gas at various percentages of CO_2 (continues).

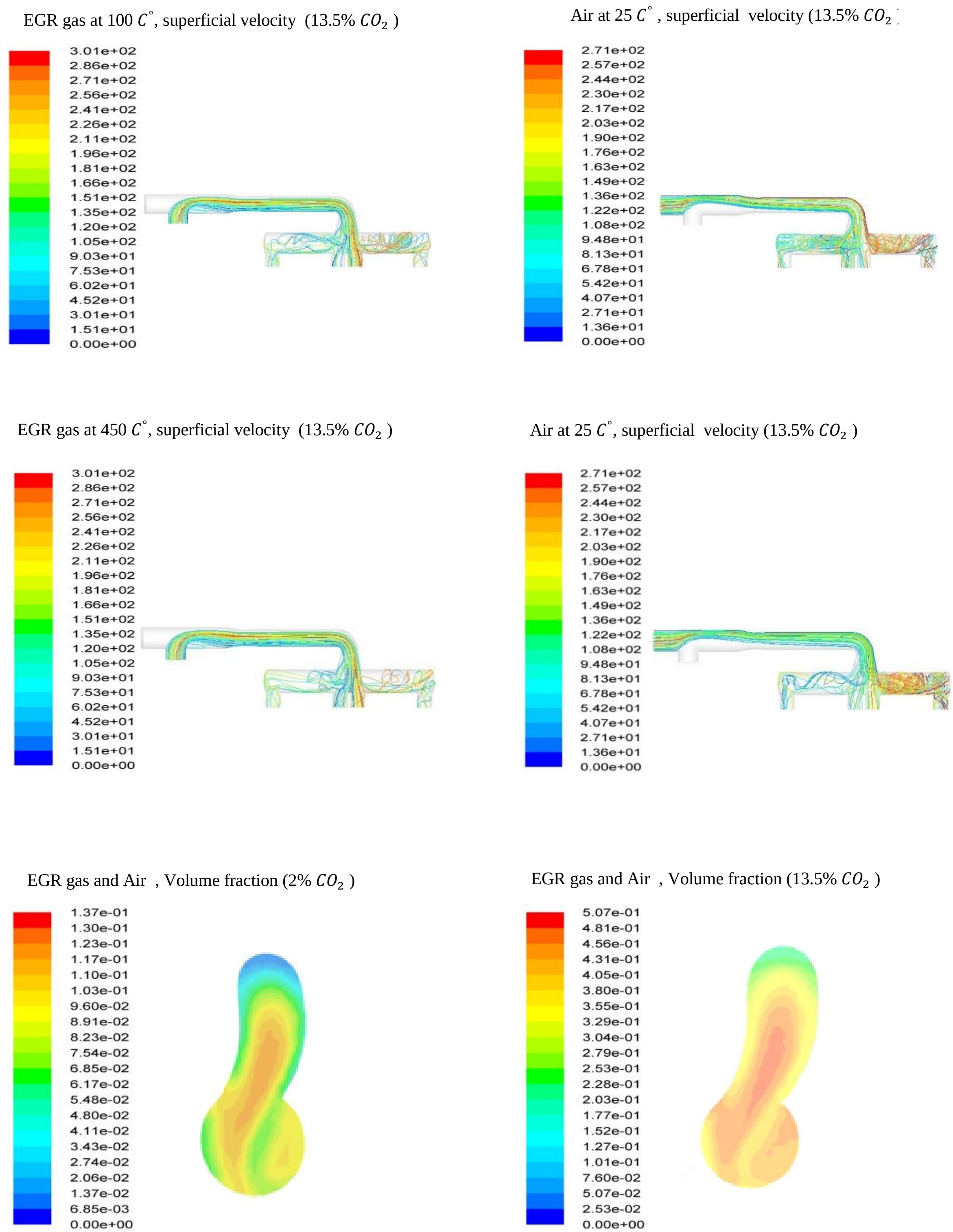

Fig. 4. Stream line and volume fraction of air and EGR gas at various percentages of CO_2 (continued) .

5 CONCLUSIONS

A combined of experimental and numerical study was carried out to investigate EGR distribution between cylinders of DI turbocharged diesel engine at various rates and in hot and cooled EGR cases. Numerical simulations were carried out with an appropriate turbulence model combined with equations for mass, momentum and energy.

The following results were obtained:

- EGR distribution is equal between cylinders for low EGR rates in hot and cooled cases.
- Cooled EGR shows better EGR distributions compared to hot EGR particularly at high EGR rates.

According to references [12-13], equal EGR distribution results in an improvement in performance and reduction NOx and PM emissions when compared to non-well-mixed air and EGR gases. Such agreement between the experimental and computed results gives confidence in the model prediction, and suggests that the model can help to improve and optimize the intake systems of future turbocharged DI engine designs. Using this method, it is possible to control emissions formation and increase of performance parameters, simultaneously.

ACKNOWLEDGEMENT

I thank and appreciate of company Tabriz Motorsazan because tests performed.

REFERENCES

1. Heywood, J.B., “Internal combustion engines fundamentals,” McGraw-Hill Education, 1998.
2. Ferguson, C.R. and Kirkpatrick, A.T., “Internal combustion engines,” Applied Thermo Sciences Wiley, 2004.
3. Zheng, M., Reader, G.T. and Hawley, J.G., “Diesel engine exhaust gas recirculation a review on advanced and novel concepts,” Energy Conversion and Management, Vol. 45, pp. 883–900, 2004.
4. Hentschel and Ritcher, W., “Time-resolved analysis of soot formation and oxidation in a directed- injection diesel engine for different EGR-rates by an extinction method,” SAE Paper, 952517, 1995.
5. Ladommatos, Abdelhalim, N., Zhao, S.M. and Hu, Z., “The dilution, Chemical and Thermal effects of exhaust gas recirculation on diesel engine emission-part4, Effects of carbon dioxide and water vapor,” SAE Paper, 971660,1997.
6. Indicheria, C.A. and Pickett, L.M., “Effect of EGR on diesel premixed-burn equivalence ratio,” Proceedings of the Combustion Institute, Vol. 31, pp. 2931–2938, 2007.
7. Hountalas, D.T., Mavropoulos, G.C. and Binder K.B., “Effect of exhaust gas recirculation (EGR) temperature for various EGR rates on heavy duty DI diesel engine performance and emissions,” Energy, Vol. 33, pp. 272–283, 2008.

8. Saleh, H.E., “Effect of exhaust gas recirculation on diesel engine nitrogen oxide reduction operating with jojoba methyl ester,” Renewable Energy, Vol. 34, pp. 2178–2186, 2009.
9. Mobasheri, R., Peng, Z. and Mirsalim, S.M., “Analysis the effect of advanced injection strategies on engine performance and pollutant emissions in a heavy duty DI-diesel engine by CFD modeling,” International Journal of Heat and Flow, Vol. 33, pp. 59–69, 2012.
10. Millo, F., Giacominetto, P.F. and Bernardi M.G., “Analysis of different exhaust gas recirculation architectures for passenger car diesel engine,” Applied Energy, Vol. 79–91, pp. 98, 2012.
11. Maiboom, A., Tauzia, X. and Hétet, J.F., “Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emission of an automotive direct injection diesel engine,” Energy, Vol. 33, pp. 22–34, 2008.
12. Maiboom, A., Tauzia, X. and Hétet, J.F., “Influence of EGR unequal distribution from cylinder to cylinder on NO_X – PM trade-off of a HSDI automotive diesel engine,” Applied Thermal Engineering, Vol. 29, pp. 2043–2050, 2009.
13. Karthikeyan, S., Hariganesh, R., Sathyanadan, M. and Krishna, S., “Computational analysis of EGR mixing inside the intake system & experimental investigation on diesel engine for LCV,” IJEST, Vol. 3, pp. 2350–2358, 2011.
14. Han, Z., Reitz, R.D., “Turbulence modeling of internal combustion engines using RNG k-Ɛ models,” Combust Sci Technol, Vol. 106, No. 4, 1995.
15. Shyy, W., “Computational modeling for fluid flow and interfacial transport,” Amesterdam, Elsevier Science, 1994.
16. Rakopoulos, C.D., Kosmadakis, G.M., Dimaratos, A.M., Pariotis, E.G., “Investigating the effect of crevice flow on internal combustion engines using a new simple crevice model implemented in a CFD code,” Appl Energy, Vol. 88, No. 1, 2011.
17. Rakopoulos, C.D., Kosmadakis, G.M., Pariotis, E.G., “Critical evaluate on of current heat transfer models used in CFD in cylinder engine simulation and establishment of a comprehensive wall-function formulation,” Appl Energy, Vol. 87, No. 5, 2010.