

# Experimental Investigation of the EGR Temperature Effects on the Destruction of the Fuel's Availability Due to Combustion Processes in IDI Diesel Engine Cylinder

**M. Ghazikhani**

Associate professor Ferdowsi University of Mashhad  
mashhad,Ferdowsi University of Mashhad  
Ghazikhani@ferdowsi.um.ac.ir

**A. Arjangnia**

Graduate student ferdowsi  
ferdowsi University of mashhad  
Amir.arjangnia@gmail.com

**M. Sharifzadeh**

PhD student ferdowsi  
ferdowsi University of mashhad  
Mohammad.sharifzade@gmail.com

**A. Sharifzadeh**

Graduate student  
Shahrood university of technology  
abolfazl.sharifzadeh@gmail.com

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Corresponding Author\*  
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## Abstract

In this study a heat exchanger is designed for cooling exhaust gas and an experiment is carried out to investigate the effect of Exhaust Gas Recirculation (EGR) temperature on destruction of the fuel's availability due to combustion processes in IDI diesel engine cylinder. To serve this aim an exergy analysis is conducted on the engine cylinder which provides all the availability terms by which the evaluation of in-cylinder irreversibilities is possible. The availability terms including heat transfer, inlet and exhaust gases and work output are presented during the engine operation at different load and speeds. To clarify the effect of using EGR in each case, EGR is introduced to the cylinder at various ratios and temperature during the tests. The results show about 60 to 70 % of fuel's availability is destroyed by irreversibilities. Also, the results reveal that the increase of EGR temperature leads to reduce of combustion irreversibility. On the other hand the increase of EGR temperature leads to heat and availability are dissipated of the wall and exhaust gas. So depend on the engine operation at different loads and speeds, the increase of EGR temperature could be lead to a positive or negative effect on the engine performance.

**Key word:** EGR (Exhaust Gas Recirculation), Fuel's Availability, Effect Temperature, Diesel Engine

## Introduction

The higher efficiency of compression–ignition–indirect injection diesel engines compared to spark-ignited gasoline engines makes them desirable for automotive and truck vehicles, especially now with the ever increasing crude oil prices, caused mainly by significant increases in demand. But a major obstacle to the extensive application of diesel engines, especially for automotive applications, is their high level of nitrogen oxides ( $\text{NO}_x$ ) and particulate emissions, both of which have possible negative effects on the environment and health. Exhaust gas recirculation, EGR, is one of the most effective means of reducing  $\text{NO}_x$  emissions from diesel engines and is widely used in order to meet the emission standards[1]. The use of high EGR rates creates the need for EGR gas cooling in order to minimize its negative impact on Engine performance especially at high engine loads where the EGR flow rate and exhaust temperature are high. Dilution of the intake air with cooled recirculated exhaust gas limits the production of in-cylinder  $\text{NO}_x$  due to a lowering of the adiabatic flame temperature and a reduction in oxygen content of the intake mixture [2]. Several works have been published that deal with the effect of EGR percentage [3-8]. But only a few works that have been published deal with the effect of EGR Temperature. On the other hand, it has long been understood that traditional first-law analysis, which is needed for modeling the engine processes, often fails to give the engineer the best insight into the engine's operation. In order to analyze engine performance – that is, evaluate the inefficiencies associated with various processes – second-law analysis must be applied. For second-law analysis, the key concept is “availability” (or exergy). The availability content of a material represents its potential to do useful work. Unlike energy, availability can be destroyed which is a result of such phenomena as combustion, friction, mixing or throttling. The destruction of availability – usually termed irreversibility – is the source for the defective exploitation of fuel into useful mechanical work in an internal combustion engine. The reduction of irreversibilities can lead to better engine performance through a more efficient exploitation of fuel[9].

In general, the introduction of EGR influences diesel engine combustion in three different ways: thermal, chemical and dilution. The thermal effect is related to the increase of inlet charge temperature that affects volumetric efficiency (thermal throttling) and the increase of charge specific heat

capacity due to the presence of  $\text{CO}_2$  and  $\text{H}_2\text{O}$ . On the other hand the chemical effect is related to the dissociation of species during combustion, while dilution is related to the reduction of  $\text{O}_2$  availability[4].

Much research has been done on first and second law analysis of diesel engine. Rakopoulos et al. [10] have compared daccumulation and destruction of exergy relative to special refrence of the limited cooled case. Caton [11] has calculated destruction of availability (exergy) due to combustion processes in an internal-combustion engine. Rakopoulos, and Kyritsis [12] have reported Comparative second-law analysis of internal combustion engine operation for methane, methanol, and deodecane fuels. Abassi et al. [13] analyzed the influence of the inlet charge temperature on the second law balance under the various operating engine speeds in DI Diesel engine. Ghazikhani et al.[4] in one experimental study have investigated effects of the Exhaust Gas Recirculation on irreversibility and Brake Specific Fuel Consumption of indirect injection diesel engines. Hosseinzadeh et al.[14] have compared thermal, radical and chemical effects of EGR gases using availability analysis in dual-fuel engines at part loads.

In this study an experiment was carried out to investigate the effect of Exhaust Gas Recirculation (EGR) temperature on on the destruction of the fuel's availability. To serve this aim an availability analysis is conducted on the engine cylinder which provides all the availability terms by which the evaluation of in-cylinder irreversibilities is possible. The availability terms including heat transfer, inlet and exhaust gases and work output are presented during the engine operation at different loads and speeds. To clarify the effect of using EGR in each case, EGR is introduced to the cylinder at various ratios and temperatures during the tests.

## Engine Specification

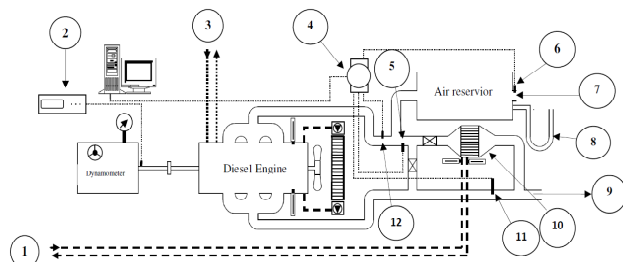
The following tests are conducted in the author's laboratory on a Perkins model 4.108 naturally aspirated, four cylinders and IDI swirl pre-chamber type diesel engine. In this experiment a heat exchanger is designed to cool exhaust gas then this heat exchanger is fitted to the engine as an external EGR system. The rate of recirculated exhaust can be controlled by a two gate-valve which one is fitted on main path and another is fitted on bypass. An oil cooling heat exchanger has been utilized in order to prevent the lubricating oil from exceeding critical temperature and the

cooling water is also circulated with an in-line pump. A surge tank and orifice system is used to measure the mass flow rate of inlet air to the engine. The power output of the test engine was measured by a hydraulic DDX Henan & Frodo dynamometer. The engine specifications are given in Table 1.

A computer interface unit is provided to measure the temperature of inlet air at the orifice, in take mixture and the exhaust gases by utilizing K-type thermocouples. Also, the pressure of the exhaust after EGR branch was recorded using Bourdon pressure gauge. Scheme of the test bed is shown in Figure 1.

**Table 1.** Specifications of diesel engine.

Engine type	4 Stroke diesel engine
Number of cylinders	4
Injection type	Indirect injection
Injection pressure (bar)	200
Bore × Stroke (mm)	79.8 × 88.9
Piston displacement (cc)	1760
Compression ratio	22:1
Maximum power (kW)	28
Maximum speed (rpm)	4500



1. Input and output Heat Exchanger cooling 2. Cyclometer 3. In and out fuel 4. Interface 5,6,11,12. Thermocouples 7. Surge tank and orifice 8. Manometer 9. Exhaust 10. Heat Exchanger

**Fig 1.** Test bed components.

### Test Procedure

The test is conducted in three engine speeds of 1500, 2000 and 3000 rpm at 75 percent of maximum achievable torque in each speed. For each test case, various EGR temperatures are examined ranging from 90 °C up to 280 °C depend on exhaust temperature. Once the percentage of load at each speed without using EGR is applied to the engine, the fuel pump rack position was kept unchanged and then the EGR ratios were setup by using the EGR valve. In each test, four EGR mass ratios of 0, 10, 20 and 30 percent were

investigated. It should also be noted that when the EGR is introduced, the engine load was slightly readjusted by the dynamometer to achieve the specified engine speed. For each case, the results of similar tests were compared and showed a good agreement which can guarantee the repeatability of experiments. The EGR percentage is defined as:

$$EGR(\%) = \frac{\dot{m}_{EGR}}{\dot{m}_i + \dot{m}_{EGR}} \times 100 \quad (1)$$

Where  $\dot{m}_{EGR}$  is the mass flow rate of recirculated exhaust gas and  $\dot{m}_i$  is the mass flow rate of fresh air [15]. In order to determine how far the EGR valve should be opened to achieve a desirable EGR mass ratio, different EGR rates were extracted from a simple computer code based on the equation of gas state and the method of trial and error. The code can estimate the air tank orifice pressure drop at a specified EGR rate by taking the engine speed, ambient conditions and intake air properties at orifice into consideration. The determination of the code in accuracy was performed and it was lower than 5%.

### General Availability Balance Equation

For an open system experiencing mass exchange with the surrounding environment, the following equation for the availability on a time basis exists [15]:

$$\frac{dA_{cv}}{dt} = \int \left(1 - \frac{T_0}{T_j}\right) \dot{Q}_j - \left(W_{cv} - P_0 \frac{dV_{cv}}{dt}\right) + \sum_{in} \dot{m}_{in} b_{in} - \sum_{ex} \dot{m}_{ex} b_{ex} - i \quad (2)$$

Where  $dA_{cyl}/dt$  is rate of change of non-flow exergy of control volume (i.e. cylinder, each manifold, etc.) availability;  $\int \left(1 - T_0/T_j\right) \dot{Q}_j$  is availability term for heat transfer, where  $\left(1 - T_0/T_j\right)$  is the efficiency of the ideal Carnot cycle working between the same temperature levels, as the process in study; and  $\dot{Q}_j$  is the time rate of heat transfer to or from the heat source.  $(W_{cv} - P_0(dV_{cv}/dt))$  is availability term associated with work transfer;  $b_{in}$  and  $b_{ex}$  availability terms associated with intake and exhaust of masses, respectively.  $b$  is defined as [15]:

$$b = b^{lm} + b^{ch} = h - T_0 s - \sum_i x_i \mu_i^o \quad (3)$$

$\dot{I}$  is rate of irreversibility production in the control volume due to combustion, throttling, mixing, heat transfer under finite temperature difference to cooler medium, etc.

Applying equation (2) to the whole engine cylinders will yield the following equation [15]:

$$\frac{dA_{cv}}{dt} = \dot{m}_{in} b_{in} + \dot{m}_{ex} b_{ex} - A_w - A_L + A_f - I \quad (4)$$

Since the data were being recorded while the engine was working on the steady state, the non-flow exergy ( $dA_{cyl}/dt$ ) is zero.

In equation (4)  $A_w$  is the rate of work shaft availability,  $A_L$  is the rate of heat loss availability to the cylinder walls,  $\dot{m}_{in} b_{in}$  and  $\dot{m}_{ex} b_{ex}$  are exergy terms of intake and exhaust gas, respectively and  $A_f$  is the rate of chemical availability associated with injected fuel. Stepanov investigated available methods for estimating chemical energies and exergies of fuels are described. One approximation for liquid fuels of the general type  $C_z H_y O_p S_q$ , applicable to internal combustion engines applications can be found in Ref. [15]:

$$a_{fch} = LHV \left[ 1.0401 + 0.01728 \frac{y}{z} + 0.0432 \frac{p}{z} + 0.2196 \frac{q}{z} \left( 1 - 2.0628 \frac{y}{z} \right) \right] \quad (5)$$

In this paper, an approximation based on the equation (5) is used for the calculation of diesel fuel chemical availability. It should be noticed that enthalpy associated with pressure of injected fuel is usually not significant and hence is ignored [15].

### First -Law Efficiency

The ratio of all the useful energy extracted from the system to the energy of the fuel input is known as first law efficiency.

But in this study it has been used from definition of brake specific fuel consumption instead of first law efficiency. By definition,

$$bsfc = \frac{\dot{m}_f}{W_{net}} \quad (6)$$

### Second-Law or Exergy or Exergetic Efficiencies

An efficiency is defined in order to be able to compare different engine size applications or evaluate various improvements effects, either from the first or the second-law perspective. The second-law (or exergy or availability) efficiency also found in the literature as effectiveness or exergetic efficiency, measures how effectively the input (fuel) is converted into product, and is usually of the form [11]:

$$\varepsilon = \frac{A_{ex} + W_{br}}{A_{fuel} + A_{air}} \quad (7)$$

Where  $A_{ex}$  is availability term for exhaust,  $W_{br}$  is brake power,  $A_{fuel}$  is availability term for fuel and  $A_{air}$  is availability term for input air.

Unlike first-law efficiencies, the second-law ones weigh the variable energy terms according to their capability for work production. Moreover, a second-law efficiency includes, in addition to exergy losses (e.g. in exhaust gases) the exergy destructions (irreversibilities) too. On the other hand, because energy is conserved, first-law efficiencies reflect only energy losses. Moreover, energy losses are not representative (and typically overestimate) the usefulness of loss. And first-law efficiencies do not explicitly penalize the system for internal irreversibilities [15].

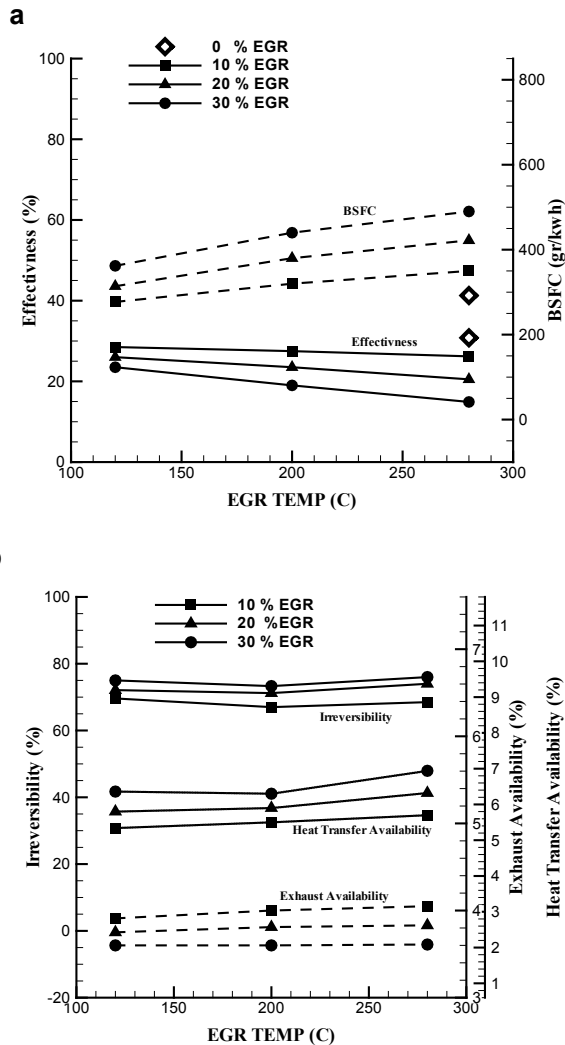
### Results and Discussions

Totally the results show about 60 to 70 % of fuel's availability is destroyed by irreversibilities, about 4 to 8 % of fuel's availability is destroyed by heat transfer to cooling water, about 2 to 5 % of fuel's availability is destroyed by exhaust and about 20 to 30 % of fuel's availability is converted to brake power. Also, the results reveal that the increase of EGR temperature leads to reduce of combustion irreversibility. On the other hand the increase of EGR temperature lead to heat and availability are dissipated of the wall and exhaust gas. So depend on the engine operation at different load and speeds, the increase of EGR temperature could leads to a positive or negative effect on the engine performance.

It is evident that the increase of EGR percentage at constant boost pressure results in a decrease in the amount of fresh air inducted per cycle. Consequently since the amount of fuel injected per cycle remains practically constant, AFR should decrease. A similar effect is expected when increasing EGR gas temperature at a given EGR rate. The negative effect of EGR on AFR increases with the increase of EGR temperature. For all cases, examining the effect of EGR rate and temperature is more pronounced at low engine speed. Thus, at full load the effect of thermal throttling (reduced amount of charge to the cylinder) is significant and increases as EGR temperature is increased to higher values.

The effect of EGR temperature and percentage on effectiveness and bsfc is presented in Figure 2.a for 3000 rpm engine speed. As shown, effectiveness is reduced linearly

with increasing EGR temperature. The decrease of effectiveness is due mainly to the increase of irreversibilities (due to increase heat loss and thermal throttling). Also reduction effectiveness with increase EGR percentage is due to increase ignition delay related to thermal and dilution effect of EGR.

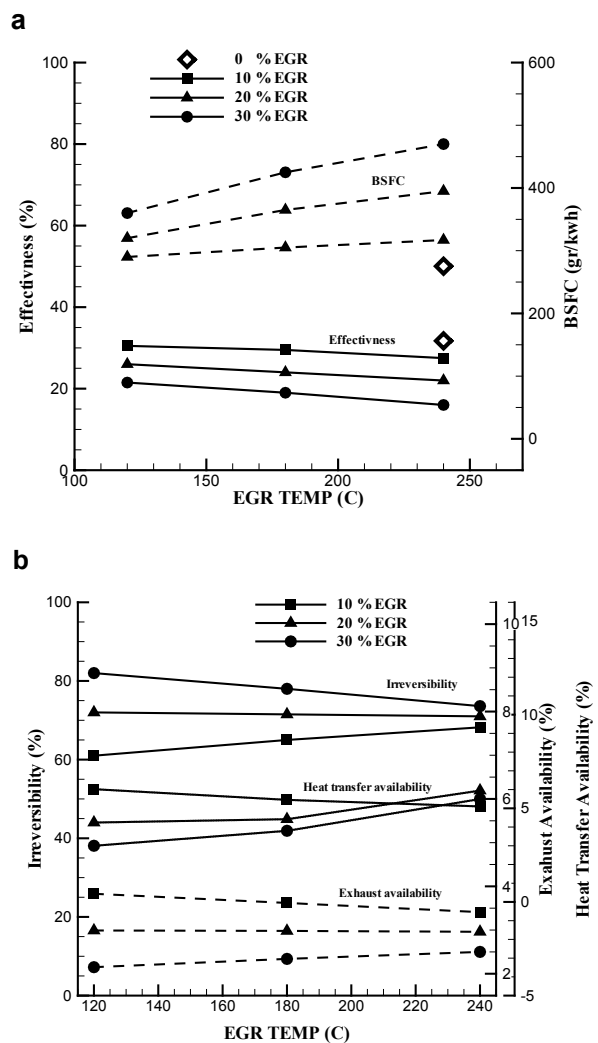


**Fig 2.** Effect of EGR temperature on effectiveness, bsfc (a) and availability terms (b) for various EGR rates at 3000 rpm

The effect of EGR temperature and percentage on availability terms is presented in Figure 2.b for 3000 rpm engine speed. As shown, irreversibility, exhaust availability and heat transfer availability are increased linearly with increasing EGR temperature. The increase of irreversibility is mainly due to the reduction of AFR ratio and the reduction of brake power. The increase of exhaust availability and heat transfer availability is due the increase of

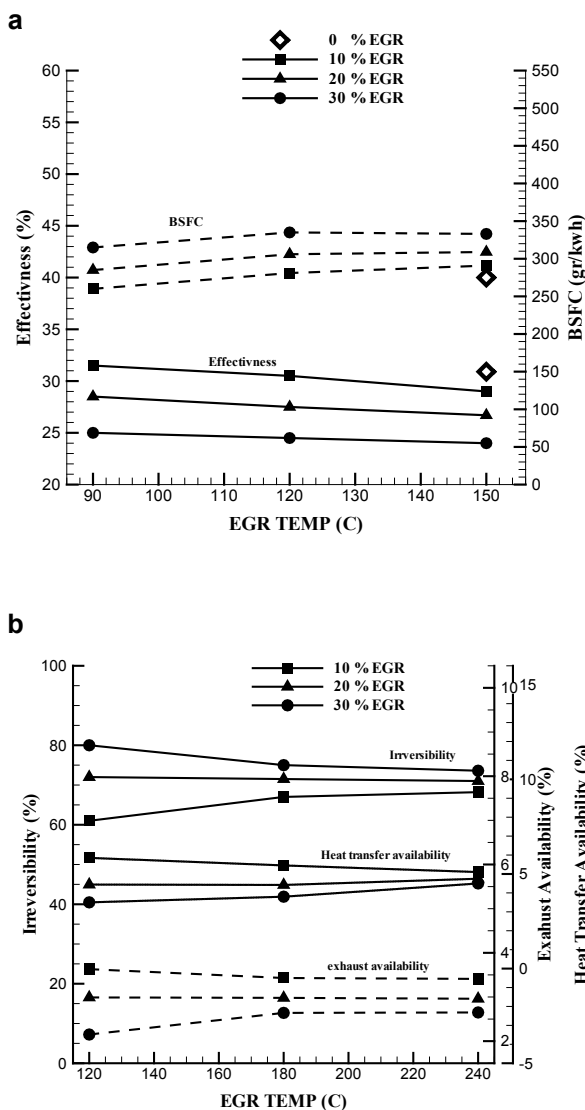
in-cylinder mean gas temperature that affects in a negative manner heat losses.

The effect of EGR temperature and percentage on effectiveness and bsfc is presented in Figure 3.a for 2000 rpm engine speed. Also the effect of EGR temperature and percentage on availability terms is presented in Figure 3.b for 2000 rpm engine speed. As shown, for 30 percent of EGR irreversibility is decreased. The decrease of irreversibility is mainly due to the reduction of entropy production due to effect of EGR heating. So for 30 percent of EGR in low speed the increase of EGR temperature has positive effect on reduction of irreversibility.



**Fig 3.** Effect of EGR temperature on effectiveness, bsfc (a) and availability terms (b) for various EGR rates at 2000 rpm

Similar results have been observed for the 1500 rpm engine speeds. At this point it should be reemphasized that the engine operates at full load where AFR is close to its lower limit. Thus the use of high EGR temperature further reduces the availability of oxygen. This lack of oxygen in the cylinder charge reduces the combustion rate leading to retarded combustion and thus to lower peak cylinder pressure values. On the other hand, the effect on ignition delay is almost negligible due to high pressure and temperature of the charge at full load resulting in very low ignition delay values.



**Fig 4.** Effect of EGR temperature on effectiveness, bsfc (a) and availability terms (b) for various EGR rates at 1500 rpm

## Conclusions

An experimental investigation was conducted to study the influence of EGR temperature on destruction of the fuel's availability due to combustion processes under various operating engine speeds in IDI Diesel engine. Various EGR temperatures and rates were examined at three different operating speeds at full load. The results show about 60 to 70 % of fuel's availability is destroyed by irreversibilities. Also the results reveal that the increase of EGR temperature in leads to the reduction in combustion irreversibility. But On the other hand the increase of EGR temperature lead to heat and availability are dissipated of the wall and exhaust gas. So depending the engine operation at different load and speeds, the increase of EGR temperature could be lead to a positive or negative effect on the engine performance.

## Latin Symbols

$A$	Non - non-flow exergy
$B$	Flow exergy
$\dot{j}$	rate of irreversibility production
$\dot{m}_{EGR}$	mass flow rate of recirculated exhaust gas
$\dot{m}_i$	mass flow rate of fresh air
$\dot{Q}_j$	time rate of heat transfer
$W$	brake power
$X$	mole fraction

## Greek Letters

$\varepsilon$	effectiveness (second-law efficiency)
$\eta$	first-law efficiency
$\mu$	chemical potential

## Abbreviations

BSFC	Brake Specific Fuel Consumption
LHV	Lower heating value
EGR	Exhaust Gas Recirculation

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