Effects of coolant temperature on the performance and emissions of a diesel engine

Waleed A. Abdelghaffar, Mohsen M. Osman, Mohamed N. Saeed
and Abdelfattah I. Abdelfattah
Mechanical Eng. Dept., Faculty of Eng., Alexandria University, Alexandria, Egypt

Experiments were conducted on a four-cylinder, four-stroke, direct-injected diesel engine to study the effects of engine coolant temperature on both performance parameters and exhaust emissions. The energy balance is discussed on the bases of first-law analysis and second-law analysis. The range of speed investigated was 1000-2000 RPM for the torque range of 25-152 N m. The coolant temperature was varied from 50 to 95 °C. The present study shows that the coolant temperature has a significant effect on the volumetric efficiency. It also shows that increasing coolant temperature decreases the mass flow rate of fuel consumption and the cooling losses. As a result, the brake specific fuel consumption decreases and the brake thermal efficiency increases. A chart was developed for showing the relationship between the coolant temperature, equivalence ratio, brake torque, and brake specific fuel consumption. The study shows that the coolant temperature has a significant effect on NO_x emissions and minor effects on the volumetric percentages of oxygen, carbon dioxide, and carbon monoxide. The unburned hydrocarbons show insignificant variation. This work also shows that increasing coolant temperature slightly increases the availability of the coolant and decreases the total availability losses.

أجريت التجارب الخاصة بهذه الدراسة على محرك ديزل حقن مباشر ورباعي الأشواط ويحتوى على أربع اسطوانات لدراسة تأثير درجة حرارة وسط التبريد على أداء المحرك وكذلك على انبعاثات غازات العادم. كذلك تم عمل الاتزان الحراري للمحرك على أسس دراسة القانونين الأول والثاني للترموديناميكا. وكان مدى السرعة فى التجارب من ١٠٠٠ إلى ٢٠٠٠ دورة/ دقيقة لمدى عزم من ٢٥ الى ١٥٢ نيوتن. متر . و تم التحكم فى درجة الحرارة بحيث ترتفع تدريجيا من ٥٠ الى ٩٥ درجة بمعدل ٥ درجات. وقيست نسب غازات العادم بواسطة جهاز خاص بتحليل غازات العادم. وقام الباحثون بعمل نموذج حسابي للاتزان الحراري للمحرك على أساس دراسة القانونين الأول والثاني للترموديناميكا. وقد أظهرت الدراسة أن درجة حرارة وسط التبريد لها تأثير واضح على معدل كمية الهواء التى يحتاجها المحرك وكذلك الكفاءة الحجمية له. وقد أظهرت الدراسة أيضا أن زيادة درجة حرارة وسط التبريد تقلل استهلاك الوقود. ونتيجة لذلك يقل معدل الاستهلاك النوعي للوقود وتزداد الكفاءة الحرارية للمحرك. وقام الباحثون أيضا بعمل خريطة توضح العلاقة بين درجة حرارة وسط التبريد ومعامل الوقود المكافئ والعزم ومعدل الاستهلاك النوعي للوقود. ولوحظ من الدراسة انه بزيادة درجة حرارة وسط التبريد تقل كمية الحرارة المفقودة الى ماء التبريد. ووجد من التجارب أن درجة حرارة وسط التبريد لها تأثير واضح على أكاسيد النيتروجين فى حين يقل هذا التأثير على نسبة الأكسجين فى غازات العادم، أول أكسيد الكربون وثانى أكسيد الكربون. بينما لا تتأثر تقريبا الهيدروكربونات الغير محترقة فى غازات العادم بدرجة حرارة وسط التبريد. وقد أظهرت الدراسة انه بزيادة درجة حرارة وسط التبريد تزداد إتاحة هذا الوسط وتقل المفقودات الكلية للإتاحية.

Keyword: Diesel engine, Coolant temperature, Performance and emissions of I.C. engine

1. Introduction

The engine coolant temperature affects engine performance, efficiency, and emissions. Lower coolant temperature increases heat transfer and reduces temperatures of the metal of cylinder head, cylinder, and piston. However, this lowers the average gas temperature and pressure, increases frictional losses, and reduces the work per cycle transferred to the piston. Thermal stresses due to temperature gradients increase with lower coolant temperatures. Changes in gas temperature due to the change in coolant temperature influence the emission formation of nitrogen oxides, carbon monoxide, carbon dioxide, and unburned hydrocarbons.

The interaction between engine coolant and engine performance can be classified, according to the literature review, into three main categories of studies:

- engine heat transfer studies,

Alexandria Engineering Journal Vol. 40(2001), No. 5, 675-685

- emission-oriented studies, and
- thermodynamic analysis studies.

The following is an account of the relevant investigations cited.

1.1. Engine heat transfer studies

Woschni [1] introduced a method for determining the heat-transfer coefficient in terms of piston speed and convection due to combustion. Taylor [2] studied the effects of operating conditions on the rate of heat transfer in a 12-cylinder liquid-cooled aircraft engine. Assanis and Heywood [3] studied diesel engines and their cooling systems in order to increase the engine efficiency to the highest possible value. Alkidas [4] studied the influences of operational parameters on the heat release and heat transfer characteristics of a divided-chamber diesel engine. Woschni and Spindler [5] studied the effect of insulating the combustion chamber wall on the rate of the heat transfer and the performance of diesel engine. Heywood [6] studied the effect of engine variables on the rate of heat transfer and the effect of coolant temperature on the temperature of the components of a spark-ignited engine. Assanis and Badillo [7] used fast-response thermocouples for heat transfer measurements in diesel engines.

1.2. Emission-oriented studies

Patterson and Henein [8] showed that increasing the coolant temperature increases NO emissions as it also reduces heat losses leading to an increase in peak cycle temperature. Scharnweber and Hoppie [9] showed that preheating the fuel prior to direct cylinder injection in diesel engines reduces particulate and NO_x emissions. Murayama et al. [10] showed that higher fuel temperatures significantly reduce the brake specific fuel consumption and smoke emissions. Kaplan and Heywood [11] found that a reduction in piston thermal capacity would reduce the total amount of unburned hydrocarbons during warm up due to the piston/liner crevice region. Miyamoto et al. [12] found that HC emissions decrease with increasing the wall temperature, while NO_x increased slightly with increases in piston wall temperature during the load increase.

1.3. Thermodynamic analysis studies

The first- and the second-law analyses in internal combustion engines have been used by investigators since the late 1950s. One of the earliest documented studies was a brief report presented by Traupel [13] in 1957. Other investigations were conducted on diesel engines such as the one by Primus and Flynn [14] and the data provided by Heywood [6]. Alkidas [15, 16] examined the application of a second-law analysis to a 2-liter, single-cylinder, direct-injection, open-chamber, diesel engine. Availability values were calculated from the thermodynamic states based on the measured values. Alasfour [17] presented the results of an availability analysis for a single cylinder, spark-ignition fuel-injected Hydra engine using both gasoline and a 30 % butanol-gasoline blend. He found at the equivalence ratio of 0.9 for the butanol-gasoline blend that 49.4 % of the fuel availability was not used to produce useful work. Caton [18-21] reported the results of a comprehensive thermodynamic cycle simulation using the approach of second-law analysis. In one portion of this study [20], a commercial, V-8, spark-ignition engine was tested at various engine loads and speeds. It was found that the availability displaced to the cylinder wall via heat transfer (as a percentage of the fuel availability) ranged between 15.9 and 31.5 %. The net availability expelled with the exhaust gases ranged between 21 and 28.1 %, and the availability destroyed by the combustion process ranged between 20.3 and 21.4 %. More details are documented in the revieus paper by caton [22].

2. Objectives of present work

The present study is concerned with the effects of coolant temperature on various performance parameters for a four-cylinder, four-stroke, direct-injected diesel engine. The effects on exhaust emissions are investigated. The energy balance is discussed on the bases of first-law analysis and second-law analysis.

3. Experimental apparatus and procedures

3.1. Engine and dynamometer

A four-cylinder, four-stroke, direct injected diesel engine was used for conducting this study. The engine has a bore of 91.4 mm, stroke of 127 mm, displacement of 3330 cm^3, nominal compression ratio of 17.4, maximum power of 48 kW at 2300 rpm, and maximum torque of 220 N m at 1350 rpm. The engine is provided with a surge tank to absorb the pressure pulsation at the intake. The engine cooler is a double-pass, liquid-liquid heat exchanger of the shell-and-tube type. The engine coolant (hot flow) is pumped through the tube pass meanwhile the city water is used as the cold flow on the shell side. The engine is coupled to a hydraulic dynamometer of the Froude type. The dynamometer is equipped with a load control, a tachometer, and a revolution counter. A schematic layout of the experimental set up is shown in fig. 1.

3.2. Instrumentation and measurements

Temperature measurements were routinely taken at nine locations: engine exhaust, engine oil, engine intake, entry and exit of engine coolant, entry and exit of tube water, and entry and exit of shell water. A thermocouple of the J-type (iron-constantan) for exhaust gas, and thermocouples of the T-type (copper-constantan) for other temperatures were assembled, calibrated, and securely installed. The thermocouples are connected to a temperature compensated digital readout through a six- channel selector. The mass flow rate of intake air was measured using an orifice meter-manometer arrangement. The mass flow rate of engine coolant was measured using a calibrated orifice meter. The exhaust gases were analyzed by an exhaust gas analyzer (Multigas- mod 488). The analyzer detects carbon monoxide, carbon dioxide, oxygen, unburned hydrocarbons, and nitrogen oxides. More details are given in the reference by Abdelghaffar [23].

3.3. Test procedures

The engine was started and warmed up for 25 to 30 minutes in order to reach steady-state operational conditions. The speed was adjusted to the required value. The flow rate of shell water through the cooler was regulated until the required coolant temperature was attained. The required engine load was obtained through the dynamometer controls. The flow rate of shell water through the cooler was decreased down to the new required coolant temperature, while the speed and the load were constant. The following quantities were routinely measured during each test:

- Intake air temperature.
- Exhaust-gas temperature.
- Engine oil temperature.
- Engine coolant temperatures.
- Tube water temperatures.
- Shell water temperatures.
- Mass flow rate of fuel.
- Mass flow rate of intake air.
- Mass flow rate of engine coolant.
- Engine rotational speed.
- Engine brake torque.
- Exhaust gas emissions (O_2, CO, CO_2, HC, NO_x).

4. Results and discussions

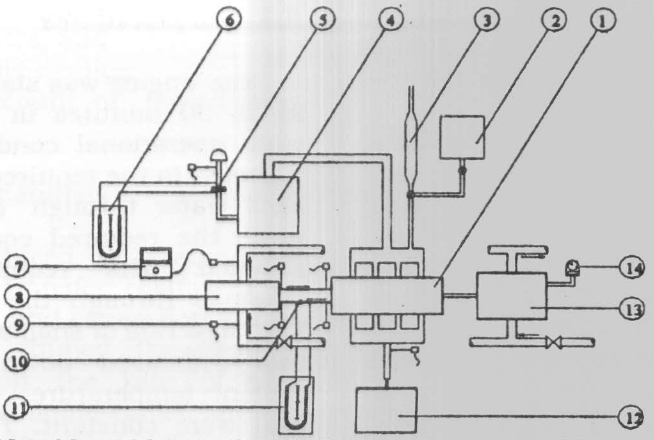
4.1. Engine performance

4.1.1. Effect of coolant temperature on volumetric efficiency

The volumetric efficiency is used as an overall measure of the effectiveness of the four-stroke cycle engine and its intake and exhaust systems as an air-pumping device. It is defined as:

$$\eta_{vol}=2\,\dot{m}_a/\rho_a.V_d.n\ . \qquad (1)$$

The effect of the engine coolant temperature on the volumetric efficiency is shown in fig. 2. The data show that the volumetric efficiency decreases with increasing the engine coolant temperature. This trend is explained by that increasing the engine coolant temperature



1.Engine 2. Fuel tank 3. Fuel burette 4. Surge tank 5. Air orifice meter 6. Intake air manometer 7. Temperature read-out 8. Heat exchanger 9. Thermocouple 10. Coolant orifice meter 11. Coolant U-tube manometer 12. Gas analyzer 13. Hydraulic dynamometer 14. Engine tachometer.

Fig. 1. Schematic layout of the experimental set-up.

leads to an increase in the cylinder wall temperature, which leads to increase the heat transfer from the wall to the relatively cold charge during the intake stroke and increases its temperature. This results in decreasing the density and the mass flow rate of air $m^{\bullet}_{a}$, which can consequently decreases the volumetric efficiency.

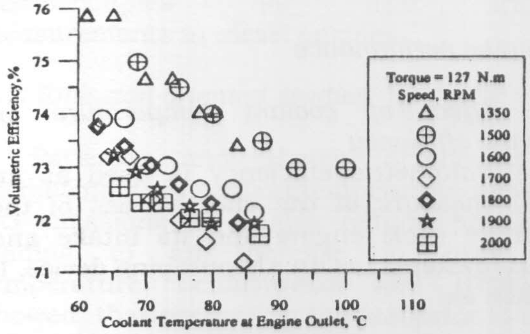


Fig. 2. Effect of coolant temperature on volumetric efficiency

4.2. Effect of coolant temperature on equivalence ratio

Mixture composition effects are usually discussed in terms of the air/fuel ratio (or fuel/air ratio) because in engine tests, the air and fuel flow rates to the engine can be measured directly and because the fuel metering system is designed to provide the appropriate fuel flow for the actual air flow at each speed and load. However, the relative proportions of fuel and air can be stated more generally in terms of the fuel / air equivalence ratio ϕ:

$$\phi = \frac{\text{actual fuel/air ratio}}{\text{stoichiometric fuel/air ratio}} . \tag{2}$$

Fig. 3 shows the effect of engine coolant temperature on equivalence ratio. The data show that the equivalence ratio decreases with increasing the engine coolant temperature. This is explained by the fact that the mass flow rate of fuel decreases by a larger rate than the corresponding decrease in mass flow rate of air.

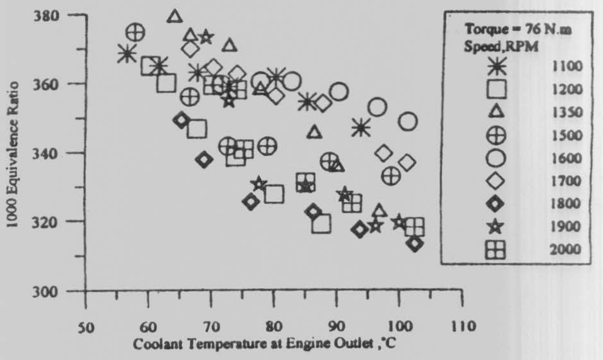


Fig. 3. Effect of coolant temperature equivalence ratio.

4.3. Effect of coolant temperature on cooling losses

Heat transfer affects engine performance, efficiency, and emissions. For a given mass of fuel within the cylinder, higher heat transfer to the combustion chamber walls will reduce the work per cycle transferred to the piston. Thus the specific power and efficiency are affected by the magnitude of engine heat transfer. The heat transfer rate $\dot{Q}$ (cooling losses) can be evaluated by:

$$\dot{Q}_c = \dot{m}_c . c_p . (T_{cout} - T_{cin}) . \qquad (3)$$

Fig. 4 shows the effect of the coolant temperature on the cooling losses as a percentage of fuel power. The data show that the cooling losses drop from about 25% at T_{cout} = 60 °C to 15% at T_{cout} close to 100 °C.

4.4. Effect of coolant temperature on brake thermal efficiency and fuel economy

The brake thermal efficiency η_{bth} is a good representation of converting fuel energy to brake power. It is defined as:

$$\eta_{bth} = \text{brake power} / (\text{fuel mass flow rate} \times \text{fuel lower heating value}). \qquad (4)$$

Fig. 5 shows the effect of engine coolant temperature on brake thermal efficiency. The data show that brake thermal efficiency increases with increasing engine coolant temperature. Increasing the coolant temperature decreases the mass rate of fuel and the equivalence ratio as shown in fig. 3, and decreases the cooling losses as shown in fig. 4, that increases brake thermal efficiency. Fig. 6 shows the effect of engine coolant temperature on Brake Specific Fuel Consumption (BSFC). The data show that BSFC decreases as the engine coolant temperature increases.

4.5. A chart for fuel economy

The data in fig. 7 show that for a constant torque of 51 N m BSFC increases with increasing the equivalence ratio. The correlation between BSFC and the equivalence ratio is given by the linear correlation:

$$\text{BSFC } (\text{g.kW}^{-1}.\text{hr}^{-1}) = \alpha\phi - \beta . \qquad (5)$$

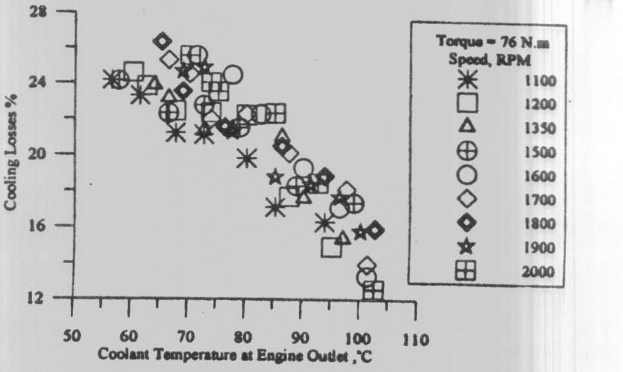


Fig. 4. Effect of coolant temperature on cooling losses as a percentage of fuel power.

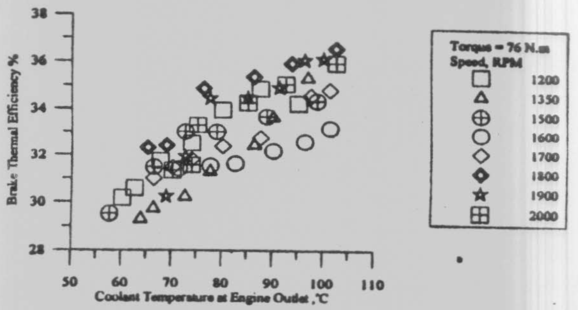


Fig. 5. Effect of coolant temperature on brake thermal efficiency.

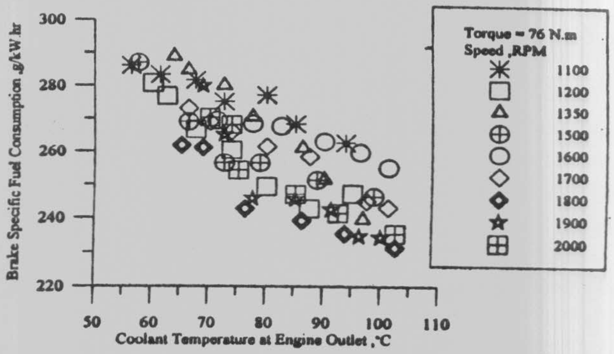


Fig. 6. Correlation of equivalence ratio and brake specific fuel consumption, $\text{g.kW}^{-1}.\text{hr}^{-1}$.

The figure also shows that the speed has no significant effect on the correlation. Other torques have been investigated and the results are shown in the chart of fig. 8 together with the effect of coolant temperature T_{cout}. The constants α and β of eq. 5 are shown in table 1.

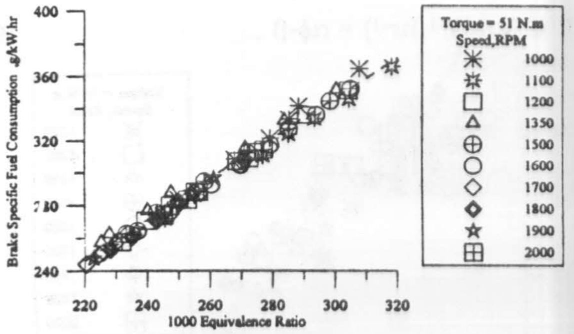


Fig. 7. Correlation of equivalence ratio and brake specific fuel consumption

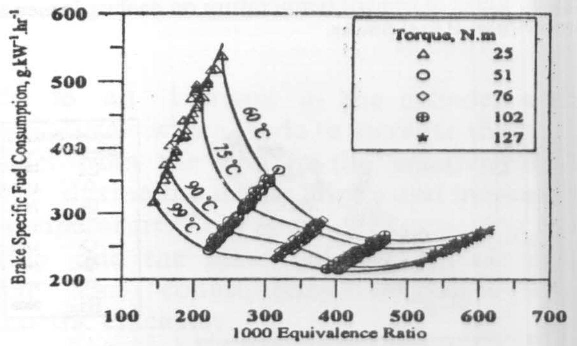


Fig. 8. Correlation of equivalence ratio and brake specific fuel consumption.

4.6. Engine emissions

4.6.1. Oxygen

Fig. 9 shows the effect of the engine coolant temperature on the volumetric percentage of oxygen in exhaust gases. The data show that the percentage of oxygen slightly decreases with increasing the coolant temperature. As the coolant temperature is increased, the charge temperature increases, which gives the chance for carbon and hydrogen in the hydrocarbon fuel to react with oxygen and improves the combustion efficiency. The data show that the volumetric percentage of oxygen in exhaust gases decreases with increasing the engine speed. This is because increasing the engine speed increases the turbulence in the combustion chamber, which leads to improve the combustion process. As a result, the volumetric percentage of oxygen in exhaust gases decreases.

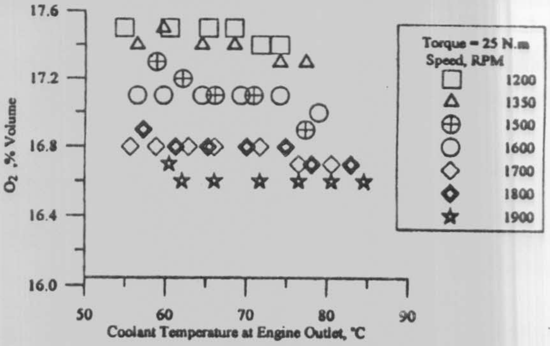


Fig. 9. Effect of coolant temperature on O2 in exhaust gases

4.6.2. Nitrogen oxides

Fig. 10 shows that NO_x emissions (PPM) increase with increasing the engine coolant temperature due to the increase in the charge temperature, which increases the burned gas temperature, which in turn leads to an increase of NO_x.

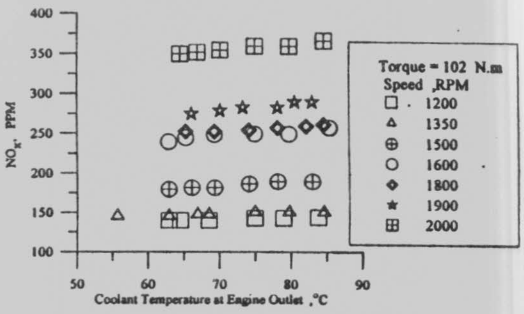


Fig. 10. Effect of coolant temperature on NO emissions.

Table 1
Correlation of eq. (5)

Engine torque, N m	25	51	76	102	127
Range of ϕ	0.142-0.238	0.220-0.318	0.313-0.379	0.385-0.467	0.517-0.614
No of data points	42	64	60	43	42
α	2397.1	1253.4	847.2	630	505.8
β	16.636	30.457	33.605	31.971	35.501

4.6.3. Carbon monoxide

Fig. 11 shows the effect of engine coolant temperature on CO (% volume). The figure shows the following:

1. The level of CO is relatively low as it comes mainly from dissociation.
2. The level of CO is nearly constant with increasing engine coolant temperature, as the increase in engine coolant temperature does not change the combustion temperature with the level that makes large variation in CO level due to dissociation.

The same trend was observed at various brake torques.

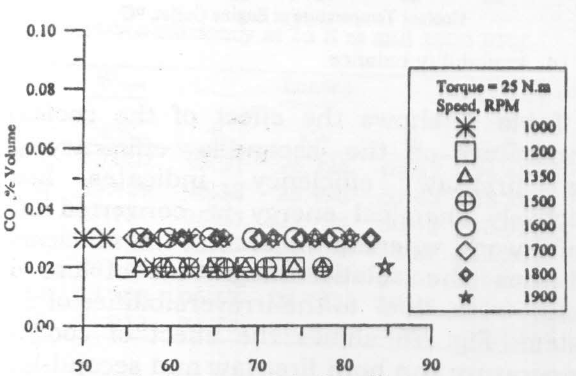


Fig. 11. Effect of coolant temperature on carbon monoxide.

4.6.4. Carbon dioxide

Fig. 12 shows the effect of engine coolant temperature on CO_2 (% volume). The data show that CO_2 slightly increases with increasing engine coolant temperature. This can be explained by the combined effect of the lean mixture and increasing charge temperature, due to increasing engine coolant temperature, on improving the combustion process, and resulted increase in CO_2.

4.6.5. Unburned hydrocarbons

Fig. 13 shows an insignificant effect of engine coolant temperature and engine speeds on unburned hydrocarbon emissions (HC) for the highest torque of 152 N m. This can be attributed to the little effect of engine coolant temperature on the mass flow rate of air and the decreasing effect of coolant temperature on the mass flow rate of fuel. Consequently, this will result in an increase in the temperature of combustion.

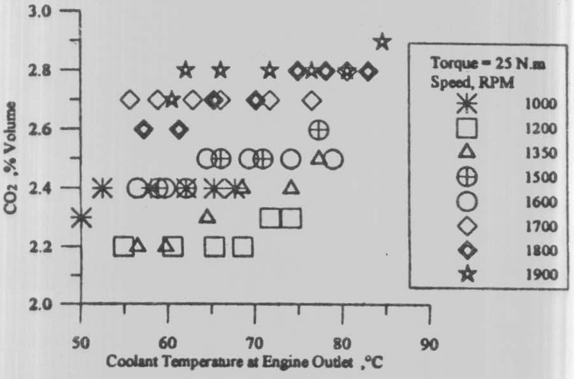


Fig. 12. Effect of coolant temperature on carbon dioxide.

4.6.6. Energy balance

First-law energy balance for an engine provides useful information on the distribution of the initial fuel energy. The steady-flow energy-conservation equation for an engine is:

$$m^{\bullet}_{f}\times L.H.V=W^{\bullet}_{b}+Q^{\bullet}_{c}+Q^{\bullet}_{ex}+Q^{\bullet}_{misc.} \qquad (6)$$

The energy balance for the engine speed of 1500 RPM and engine torque of 76-N m is shown in table 2. This table shows that the reduction of the heat losses would allow a fraction of the heat transferred to the combustion walls to be converted to useful work, which is represented by increasing in η_{bth}. The remainder would leave the engine as sensible exhaust enthalpy, which is represented by increasing in $Q^{\bullet}_{ex}$. The data shown in table 2 are plotted in fig. 14.

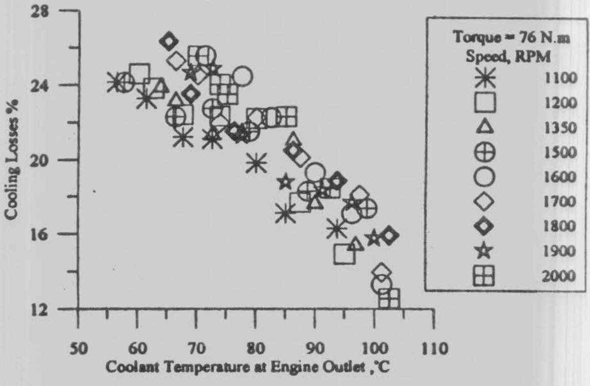


Fig. 13. Effect temperature at engine outlet, °C.

4.6.7. Availability balance

The maximum brake power that can be extracted from the system may be obtained from the application of the second law of thermodynamics (availability balance). This is given as:

$$W_{max}=A_f+A_c+A_{env}+A_{int}-A_{ex}\ . \tag{7}$$

Several significant observations can be made from these results:

- For the same fuel input, the brake power increases with increasing the coolant temperature.
- The availability of the exhaust slightly decreases with increasing the coolant temperature due to the decrease in exhaust temperature.
- Next to the brake power availability, the exhaust availability is the most important.
- The availability loss, which is a result of the irreversibilities of the system, such as heat transfer, friction, mixing, and combustion, appears to be very significant, and decreases with increasing the coolant temperature.

The availability balance at 76 N m and 1500 RPM is shown in fig. 15.

An alternative way to examine the loss of availability from the engine is to consider the second-law efficiency η_{II}, which is defined as:

$$\eta_{II}=W/W_{max}=1-A_{loss}/W_{max}\ . \tag{8}$$

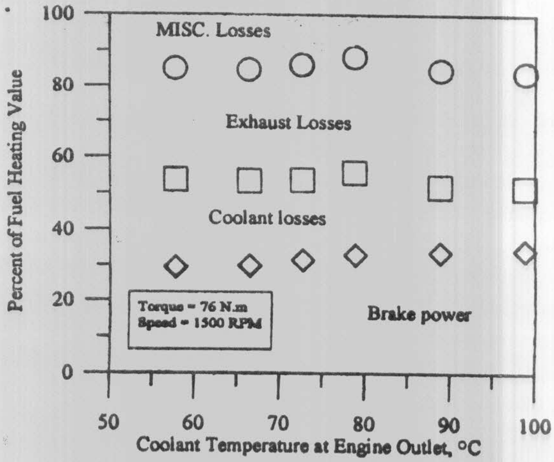


Fig. 14. Availability balance.

Table 4 shows the effect of the coolant temperature on the second law efficiency η_{II}. The first-law efficiency indicates how effectively chemical energy is converted into useful work, whereas the second-law efficiency indicates the relative magnitude of loss of useful work due to the irreversibilities of the system. Fig. 16 shows the effect of coolant temperature on both first-law and second-law efficiencies.

Table 3
Availability balance at 76 N m and 1500 RPM as a percentage of fuel availability

	Input %			Output %					
T_{cout}, C	Fuel	Intake	TOTAL	Brake	Exhaust	Coolant	Environment	TOTAL	Losses %
57.7	100	0	100	28.55	6.91	2.13	0.00	37.58	62.42
62.6	100	0	100	28.99	7.00	2.38	0.00	38.37	61.63
66.4	100	0	100	30.45	6.64	2.49	0.00	39.58	60.42
72.6	100	0	100	31.93	6.79	2.90	0.00	41.63	58.37
78.8	100	0	100	31.93	6.93	3.07	0.00	41.93	58.07
88.8	100	0	100	32.58	6.88	3.05	0.00	42.51	57.49
98.7	100	0	100	33.23	6.53	3.27	0.00	43.04	56.96

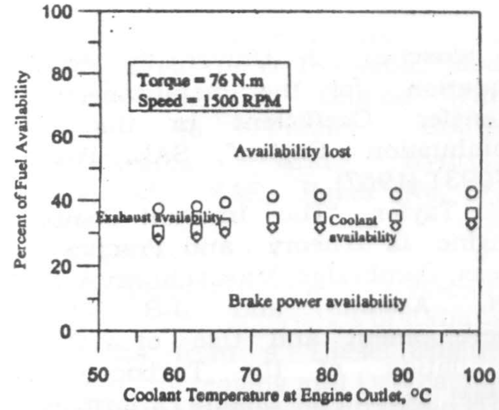


Fig. 15. Temperature at engine outlet, °C.

Table 4
The second-law efficiency at 76 N m and 1500 RPM

	W_{max}		Losses		
T_{cout}	kW	%	kW	%	η_{II}%
57.70	40.007	95.21	26.226	62.42	34.45
62.68	39.459	95.38	25.498	61.63	35.38
66.41	37.757	95.85	23.798	60.42	36.97
72.64	36.095	96.10	21.923	58.37	39.26
78.86	36.110	96.14	21.808	58.07	39.61
88.82	35.398	96.17	21.161	57.49	40.22
98.78	34.913	96.74	20.556	56.96	41.12

5. Conclusions

1. The volumetric efficiency decreases with increasing the coolant temperature.
2. The mass flow rate of fuel consumption decreases with increasing the coolant temperature. As a result, the brake specific fuel consumption decreases and the brake thermal efficiency increases.
3. A chart was developed (Fig. 7) for the relationship between the brake specific fuel consumption and the equivalence ratio at various brake torque and various coolant temperatures.
4. A correlation between the brake specific fuel consumption and the equivalence ratio is proposed on the basis of the present work as:

BSFC (g kW^{-1} hr^{-1}) = $\alpha\phi - \beta$
where the constants α and β depend on the range of ϕ and are shown in table 1. The engine speed has no significant effect on the correlation.
5. The cooling losses, as a percentage of the fuel power, decrease with increasing the coolant temperature. The results show that, for constant engine torque and speed, the cooling losses drop from about 25% of fuel power at T_{cout} = 60 °C to 15% of fuel power at T_{cout} close to 100 °C.
As the coolant temperature increases, the volumetric percentage of oxygen in the exhaust gases slightly decreases, the NO_x emissions (PPM) increase, the level of carbon monoxide is nearly constant, the volumetric percentage of carbon dioxide slightly increases, and the unburned hydrocarbons show insignificant variation.

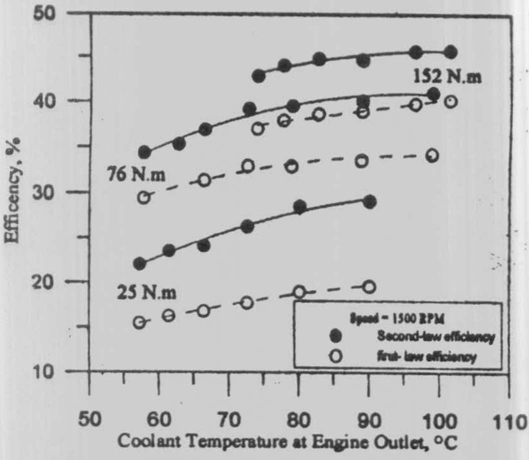


Fig. 16. Effect of coolant temperature on the first a and second-law efficiencies.

6. For the same brake torque and engine speed, the second-law analysis shows the following effects of increasing the coolant temperature:
- the required fuel decreases as much as 14 %,
- the second-law efficiency can increase by about 6 %,
- the availability of the coolant increases by 1 %,
- the availability of the exhaust gases slightly decreases, and
- the percentage of total availability losses decreases by about 5 % and above.

Acknowledgments

The authors would like to thank the staff of the Internal Combustion Engines Laboratory of the Faculty of Engineering, Alexandria University.

Nomenclature

Symbols

$A^{\bullet}$	Availability rate
A / F	Air- Fuel mass ratio
BSFC	Brake specific fuel consumption
C_p	Specific heat at constant pressure
L.H.V.	Lower heating value of fuel
$M^{\bullet}$	Mass flow rate
N	Engine speed
$Q^{\bullet}$	Rate of heat transfer
T	Temperature
V_d	Engine displacement
W	Work
$W^{\bullet}$	Power

Greek Letters

ϕ	Equivalence ratio
ρ	Density
η	Efficiency
η_{II}	Second-law efficiency

Subscripts

A	Air
A,th	Theoretical air
B	Brake
B,max	Brake, maximum
B,th	Brake, thermal
C	Coolant
Cin	Coolant inlet
Cout	Coolant outlet
Env	Environment
Ex	Exhaust
F	Fuel
G	Gas
Int	Intake
Loss	Loss
Max	Maximum
Misc	Unaccountable miscellaneous losses
Vol	Volumetric

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Received July 5, 2001
Accepted August 19, 2001