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Development of a Jet Engine Experiment for the Energy Systems Laboratory

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Abstract

Recently, a jet engine experiment was added to the Energy Systems Laboratory at Kettering University (formerly GMI). The educational objectives of this experiment are: to familiarize the students with the operation of a turbojet engine, the theory behind the thermodynamic processes involved, and the linear momentum equation; to determine theoretical and measured engine thrust and the efficiencies of the compressor, the combustion chamber, and the turbine; to determine the effect of engine speed on thrust-specific fuel consumption (TSFC) and engine emissions; to analyze the combustion process; and to perform a complete energy balance on the jet engine. The apparatus used is a small TTL model SR-30 turbojet engine capable of kerosene and diesel liquid fuel start and operation. Using an automatic data acquisition system, the students operate the engine at 50,000-75,000 rpm and measure various pressures and temperatures as well as fuel flow rate, air flow rate, engine emissions and engine thrust. The data is then used to calculate the TSFC, component efficiencies and the A/F ratio. By using the linear momentum principle, engine thrust is calculated and compared with the measured value. This paper presents the measured test data and analytical results obtained by using the Engineering Equation Solver (EES). Experimental results compare favorably with theoretical predictions.

Nomenclature:

A	area
A/F	air-fuel ratio
F_T	thrust force
h	specific enthalpy
η_C	compressor efficiency
η_{CC}	combustion chamber efficiency
η_T	turbine efficiency
k	specific heat ratio
lhv	lower heating value of fuel
M	Mach number
$\dot{m}$	mass flow rate
p	absolute pressure
$\dot{Q}_{in}$	rate of heat release by fuel
$\dot{Q}_{loss}$	rate of heat loss
q_t	turbine heat gain
R	gas constant
ρ	density
s	specific entropy
T	absolute temperature
v	velocity
w	specific work

Subscripts:

a	ambient air / diffuser inlet
a+f	air plus fuel (exhaust)
i	ideal state
0	stagnation
1	diffuser exit / compressor inlet
2	compressor exit / combustion chamber inlet
3	combustion chamber exit / turbine inlet
4	turbine exit / nozzle inlet
5	nozzle exit

Introduction:

Recently, a small TTL model SR-30 turbojet engine [1] was added to the *Energy Systems laboratory* at Kettering University (formerly GMI Engineering & Management Institute), a fully cooperative institute that offers degree programs in engineering, sciences and management. The Jet Engine Experiment utilizing this equipment has the following educational objectives:

- To familiarize the students with the operation of a turbojet engine, the theory behind the thermodynamic processes involved, and the linear momentum equation.

- To determine theoretical values of engine thrust and the actual efficiencies of the compressor, the combustion chamber and the turbine.

- To determine the effect of the "specific heat ratio, $k = c_p/c_v$" on the calculated results.

- To determine the effect of engine speed on the thrust force, thrust-specific fuel consumption, air-fuel ratio and engine emissions.

- To compare the thrust specific fuel consumption of this engine with the thrust specific fuel consumption of commercial jet engines.

- To perform an energy balance on the jet engine.

The SR-30 turbojet has been incorporated into many laboratories worldwide and several authors have published their experiences with this machine [2-4]. This engine is shown schematically in Figures 1-3.

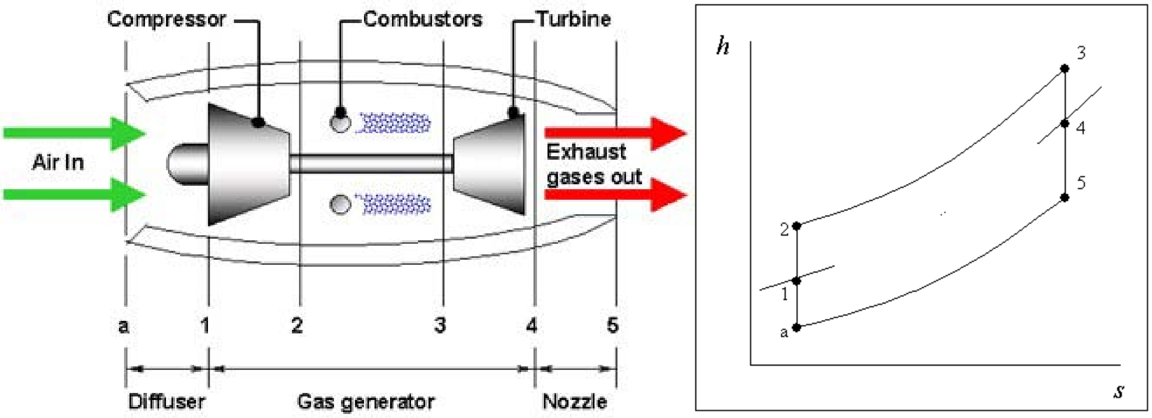


Figure 1: Schematic diagram of a jet engine and the associated ideal cycle

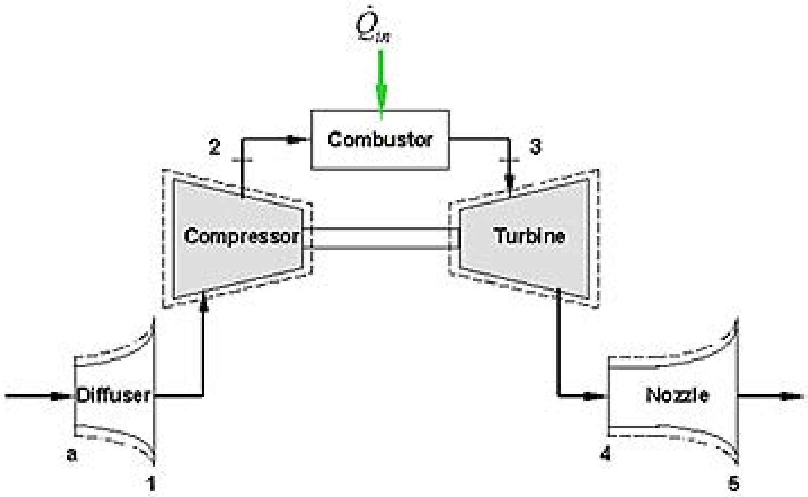


Figure 2: Schematic diagram of a jet engine

A large amount of atmospheric air is continuously brought into the engine diffuser or intake. After the diffuser, the air passes through the compressor and the combustion chamber. The hot exhaust gases leaving the combustion chamber pass through the turbine. Turbine work is used to operate the compressor through a linking shaft. The gases leaving the turbine accelerate through the nozzle. The exhaust velocity is much greater than the free stream velocity; hence a thrust force is created.

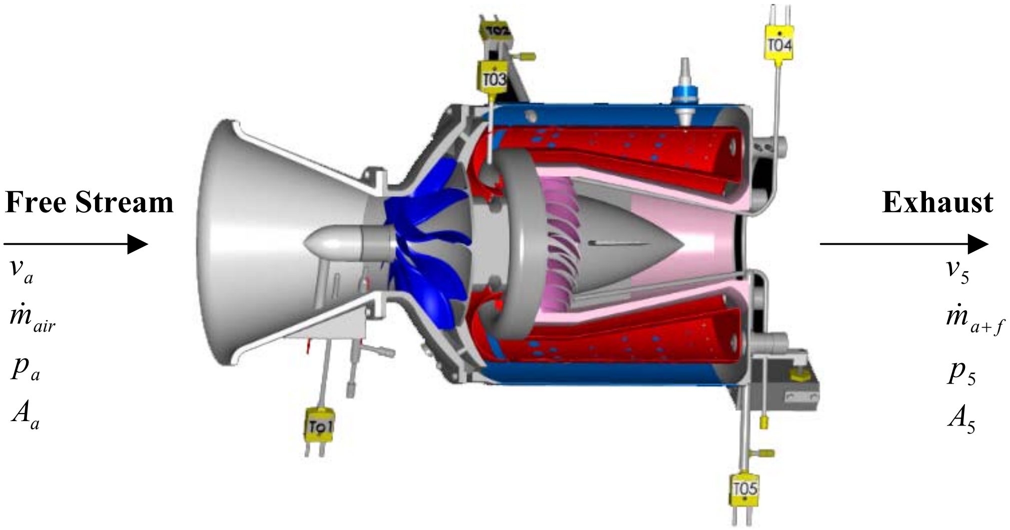


Figure 3: Cross sectional view of the turbojet engine used in this experiment (Courtesy of Turbine Technologies)

<u>Hardware Modifications</u>:

During initial testing of the SR-30, the measurement of thrust, fuel flow rate and engine speed were found to be inadequate and the system had no airflow measurement capability.

The thrust measurement was not accurate enough due to two factors: over-constrained engine support, and a primitive load transducer. The jet engine was supported on two "legs". The front leg was attached to the floor of the test stand, while the rear leg was not attached. This support did not allow the jet engine to thrust against the load transducer. Furthermore, the rear leg, although not bolted, did not move freely with respect to the floor. The load transducer was a simple strain gauge unit that is not commercially produced. This device had no temperature compensation and had a low output sensitivity. It was also attached to the front support leg, well below the centerline of the thrust. The net effect was that the load measurement did not maintain zero and the resolution was inadequate. In order to improve the thrust measurement both the engine support system and the load transducer were replaced.

To provide for freer engine response to thrust, the engine was hung from an external frame using four straps made from steel shim stock. This is shown in Figures 4 and 5. The support legs were retained in order to provide a convenient mount for the hanging supports; the unit has been raised up about ½ inch off the floor so that the legs do not touch the floor. The straps provide little resistance to axial thrust, while preventing the system from twisting or moving laterally. In order to improve the thrust response even further, all of the rigid tubing connections were replaced with flexible couplings.

The load transducer was replaced with a commercially available standard load cell rated to 25 lb_f (Omega LC101-25). As installed, the thrust measurement accuracy is better than 0.1 lb_f. This unit was selected because of its high sensitivity response to excitation voltage (3 mV/V). The typical load cell sensitivity is 2 mV/V. Further, it is temperature compensated and has good accuracy and linearity. The load cell is mounted so that it resists the thrust, in compression, as near to the thrust centerline as is practical. The jet engine is restrained axially by the load cell.

In order to calibrate the thrust measurement, a cable-pulley system was devised so that calibrated weights could be hung from the centerline of the jet engine. The system calibrated to a resolution of better than 0.1 lbs. The thrust measurement system also maintains zero and is repeatable with load increases or decreases.

Figure 4: Modified support system, front view

Figure 5: Modified support system, rear view

The fuel flow rate is determined by using a direct gravimetric approach. The weight change of fuel used is measured using a Weigh-Tronix WI-125sst scale. The air flow rate is determined in SCFM (standard cubic feet per minute) by using a Sierra 780S Flat-Trak Mass Air Meter (Calibrated Ranges:600 scfm and 200 scfm; Accuracy: ± 2% of reading from 10 to 100% of calibrated range & ± 0.5 % of full scale below 10% of calibrated range). The original system used a frequency to voltage circuit to convert the engine speed to an analog voltage. This was replaced with a direct frequency counter that outputs both a digital display and analog voltage. Emissions measurements were made using a Horiba MEXA 7100D system, pictured in Figure 6. The emissions sample is drawn through a heated trace line and filter.

Figure 6: View of the Horiba MEXA 7100D system

Analytical Treatment:

Applying the linear momentum principle to the entire engine (steady state) we obtain:

$$F_T = \dot{m}_{a+f} v_5 - \dot{m}_{air} v_a + (p_5 - p_a) A_5$$

The first term $(\dot{m}_{a+f} v_5)$ is the **gross thrust**; the second term $((\dot{m}_{air} v_a)$ is the **ram drag**. The **net thrust** equals gross thrust minus ram drag. If the nozzle exit pressure (p_5) is higher than the free stream pressure (p_a) additional thrust is produced.

Compressor Work:

It is assumed that the compressor is adiabatic. The process is isentropic in an ideal compressor:

$s_{02i} = s_{01}$

For an adiabatic compressor, the compressor work per unit mass of air (w_{1-2}) is equal to the change in the specific stagnation enthalpy of the air from the entrance to the exit of the compressor.

$w_{1-2} = h_{02} - h_{01}$

The enthalpies at the entrance and exit are functions of the compressor inlet and exit temperatures.

Compressor Efficiency (η_C) is given by:

$$\eta_C = \frac{h_{02i} - h_{01}}{h_{02} - h_{01}}$$

Compressor Efficiency (η_C) is used to account for the actual performance of the compressor as opposed to the ideal, isentropic compressor (Figure 7).

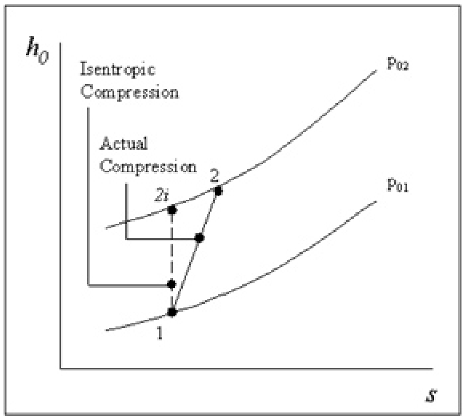


Figure 7: Comparison of isentropic and actual compression

Rate of Heat Release by the Fuel:

The heat released by the fuel is the amount of energy input into the engine. It can be found by multiplying the lower heating value of the fuel and the mass flow rate of the fuel entering the combustion chamber. Once the total energy input is found, we can find the efficiency of the combustion chamber (Figure 8).

$$\dot{Q}_{in} = \dot{m}_{fuel} \cdot lhv$$

$$\eta_{cc} = \frac{(\dot{m}_{a+f} \cdot h_{03}) - (\dot{m}_{air} \cdot h_{02})}{\dot{m}_{fuel} \cdot lhv}$$

$$A/F = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$$

$$\dot{m}_{a+f} = \dot{m}_{air} + \dot{m}_{fuel} \cong \rho_{air} \cdot A_5 \cdot v_5$$

(We can assume the density of exhaust is the same as air.)

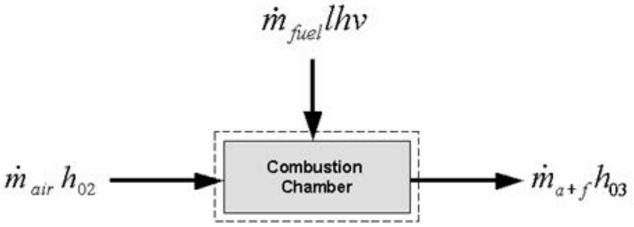


Figure 8: Schematic diagram of combustion chamber

Thrust Specific Fuel Consumption:

Thrust specific fuel consumption is used to determine the amount of fuel, in kilograms, consumed by an engine while producing one kilo-Newton of thrust during one hour of operation.

$$TSFC = \frac{\dot{m}_f}{F_T} \left(\frac{kg/hr}{kN}\right)$$

Turbine Work and Heat Gain:

The turbine is in the vicinity of the combustion chamber and receives a significant amount of heat. It is assumed that the work of this ***non-adiabatic turbine*** is equal to the compressor work.

$w_{3-4} = w_{1-2}$

The heat gained by the turbine is:

$q_t = w_t-(h_{03}-h_{04})$

For an ideal turbine, the process is isentropic:

$s_{04i} = s_{03}$

The turbine Efficiency is found from (Figure 9):

$$w_{3-4} = \eta_T \left(h_{03} - h_{04i} \right)$$

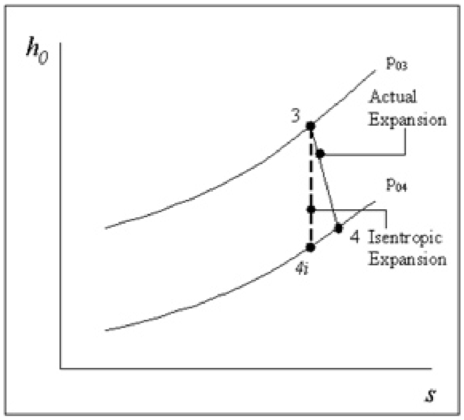


Figure 9: Comparison of isentropic and actual expansion

Nozzle Exit Velocity:

Since the nozzle exit pressure (p_5) is equal to the barometric pressure and the nozzle exit stagnation pressure (p_{05}) is measured, the ratio $(p/p_o)_5$ can be determined. Using this ratio, the nozzle exit Mach number and the temperature ratio $(T/T_o)_5$ are found from the *isentropic flow relations*. The nozzle exit velocity (v_5) is then found from the following equations:

$$\left(\frac{P_0}{P} \right)_5 = \left[1 + \left(\frac{k-1}{2} \right) M_5{}^2 \right]^{\frac{k}{(k-1)}}$$

$$\left(\frac{T_0}{T} \right)_5 = 1 + \left(\frac{k-1}{2} \right) M_5{}^2$$

$$v_5 = M_5 \sqrt{kRT_5}$$

Energy Balance:

The energy balance for the entire jet engine connected to a stationary test stand is based on the schematic diagram shown in Figure 10.

The heat released by the fuel ($\dot{Q}_{in}$) is used to:

1. cause an increase in kinetic energy
2. cause an increase in enthalpy

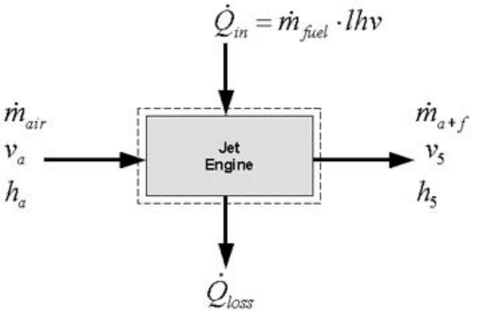


Figure 10: Schematic diagram of a jet engine as an open system.

3. overcome heat losses from the engine

Most of the heat input is used to produce the enthalpy of the exhaust gases; some is used to increase the kinetic energy of the exhaust and the rest is lost by convection and radiation.

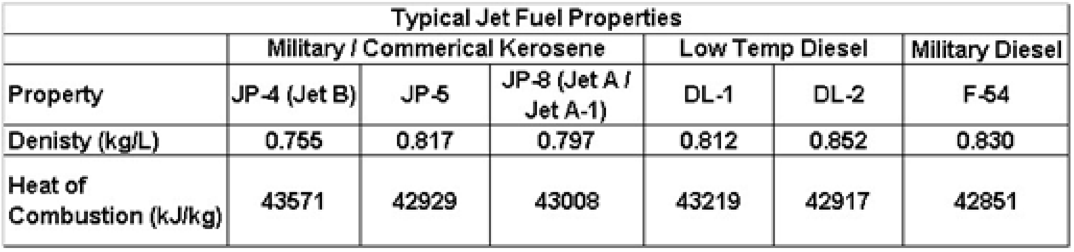
$$\underbrace{\dot{m}_{fuel}lhv}_{\substack{\text{Heat}\\ \text{Input}}} = \underbrace{\dot{m}_{a+f}\frac{v_5^{\,2}}{2}}_{\substack{\text{Kinetic}\\ \text{Energy}}} + \underbrace{\left(\dot{m}_{a+f}h_5 - \dot{m}_{air}h_a\right)}_{\substack{\text{Enthalpy}\\ \text{Change}}} + \underbrace{\dot{Q}_{loss}}_{\substack{\text{Heat}\\ \text{Loss}}}$$

All above equations are solved simultaneously by using the EES software [5].

Fuel Specifications:

The SR-30 turbojet engine is capable of running several grades of jet fuel, including military and commercial grades of kerosene and diesel fuel.

Table 1 lists the various types of fuel that can be used. It also shows the density and heat of combustion for each fuel. Please note that JP-4 and JP-8 are military equivalents for similar commercial fuels Jet B and Jet A / Jet A-1.



Typical Jet Fuel Properties						
	Military / Commerical Kerosene			Low Temp Diesel		Military Diesel
Property	JP-4 (Jet B)	JP-5	JP-8 (Jet A / Jet A-1)	DL-1	DL-2	F-54
Denisty (kg/L)	0.755	0.817	0.797	0.812	0.852	0.830
Heat of Combustion (kJ/kg)	43571	42929	43008	43219	42917	42851

Table 1: Jet fuel properties

Procedure Used by the Students:

- Follow the "Pre-Start Checklist" and "Starting Procedure" to start the engine.
- Use the automatic data acquisition system to measure (p_0, T_0, F_T, etc…) at four different engine speeds (at steady state). Also collect emissions data.
- Import the data to a spreadsheet.
- Calculate the TSFC, compressor efficiency, combustion chamber efficiency, turbine efficiency, and the A/F ratio for each engine speed.
- Using the linear momentum principle, calculate the engine thrust and compare with the measured value.
- Plot the actual thrust force versus engine speed.
- Plot the TSFC versus engine speed.
- Plot the A/F ratio versus engine speed.

- Plot NO_X , THC and CO emissions (ppm) versus engine speed.
- Make an energy balance pie chart at one engine speed.
- Compare the theoretical and actual values of the SR-30 engine thrust and discuss any differences.
- Discuss the effect of engine speed on actual thrust force, thrust-specific fuel consumption and engine emissions.
- Compare the thrust-specific fuel consumption of this engine with TSFC of large commercial engines.
- Comment on the energy balance pie chart.

The Results:

Steady state data were collected at four engine speeds ranging from 48,830 to 76,848 rpm. These data were analyzed by using EES software [5].

The Gas Constant

Originally, the gas constant (R) for pure air was used to calculate the nozzle exit velocity. This velocity was then used to determine the kinetic energy change across the engine and the theoretical thrust force. However, this is slightly inaccurate as combustion products are expelled from the jet engine. For this reason, a new gas constant value was calculated for each engine speed (RPM) based on the exhaust gas composition. The Jet-A fuel was approximated as kerosene, $C_{12} H_{26}$. Based on a complete combustion process, the value of (R) for the exhaust gases was determined for air/fuel ratios ranging from 15 to 100. The result is shown in Figure 11. The value of R decreases slightly with air/fuel ratio in the range f interest.

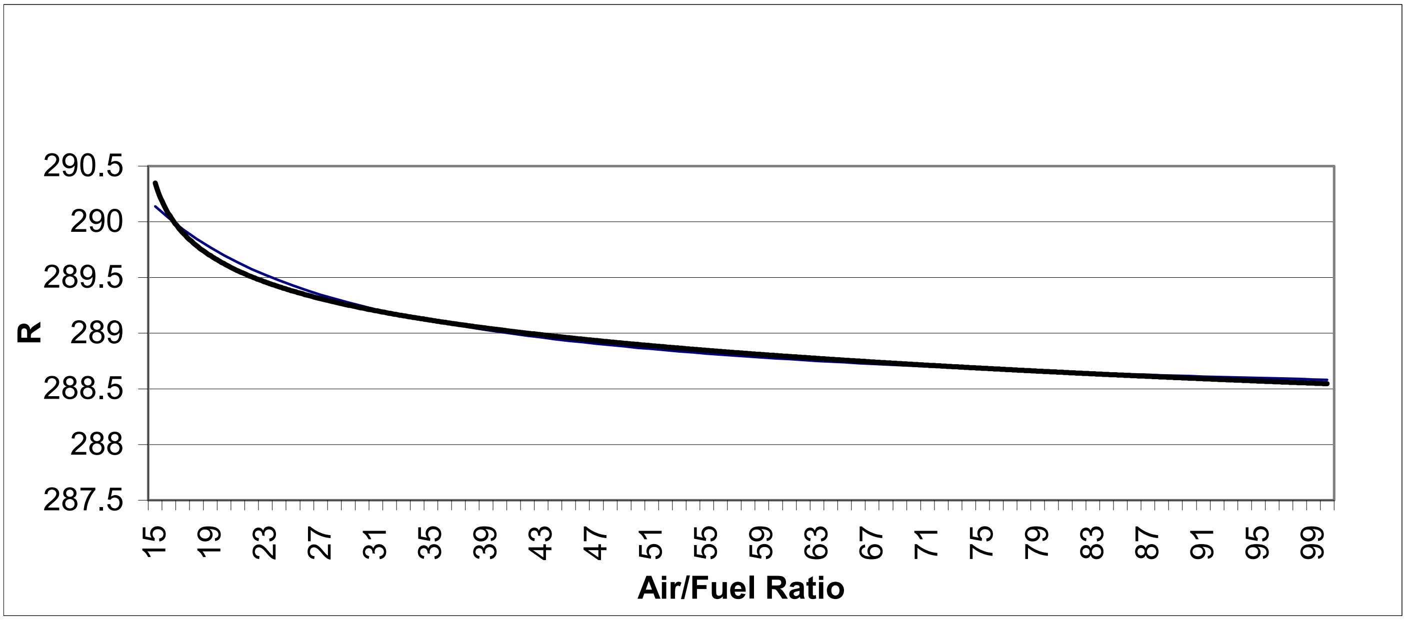


Figure 11: The gas constant (R) versus air/fuel ratio

Thrust Force and the TSFC

The thrust force and the thrust specific fuel consumption are shown in Figures 12-14. Both actual and theoretical thrust forces increase with engine speed as expected. Based on the data collected, the actual thrust was greater than the theoretical thrust. This can only be attributed to measurement errors. The value used for the specific heat ratio (k) had little effect on the results.

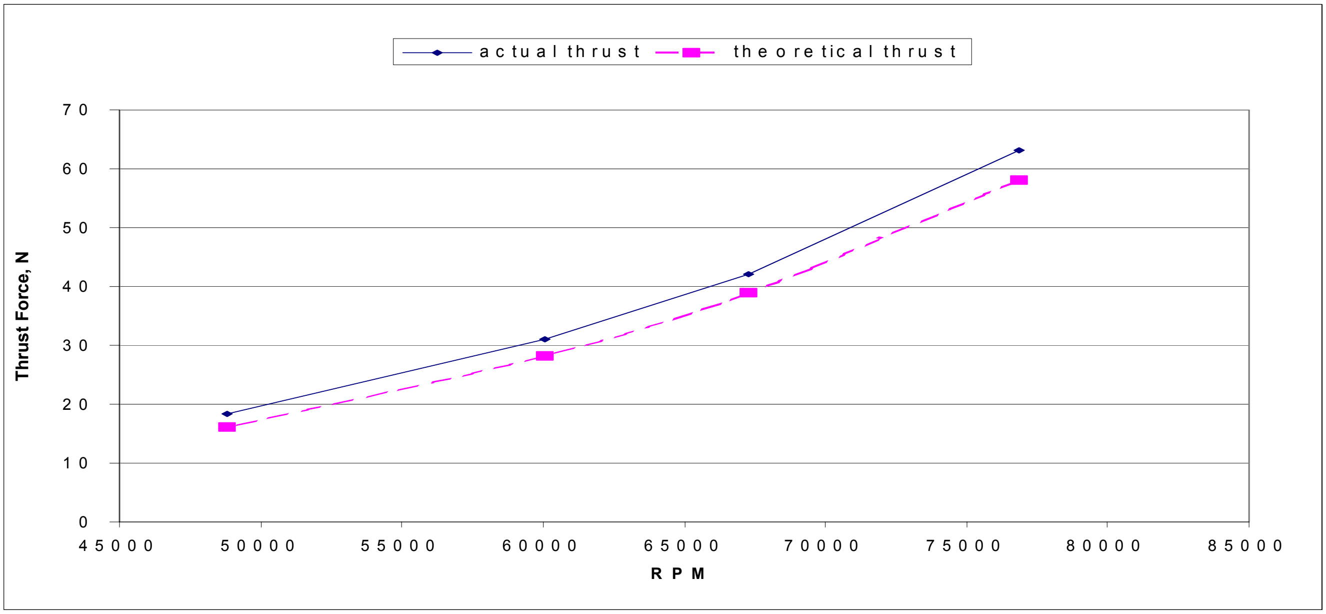


Figure 12: Actual and theoretical thrust force versus engine speed

The TSFC decreases significantly with engine speed (Figure 13) and combustion chamber temperature (Figure 14). This indicates a more fuel-efficient engine at high speeds and combustion temperatures. When comparing the TSFC of the SR-30 engine with that of large commercial engines [6-8] it was found that the SR-30 engine is much less efficient. Average TSFC for the SR-30 engine is about 310 kg/hr/kN (3.1 lbm/hr/lbf) whereas large commercial engines have typical TSFC values of between 1.0 and 1.3 lbm/hr/lbf. This indicates that the SR-30 requires more fuel to produce the same amount of thrust compared to a large commercial engine. This is, of course, expected because the SR-30 is a small engine designed for educational use.

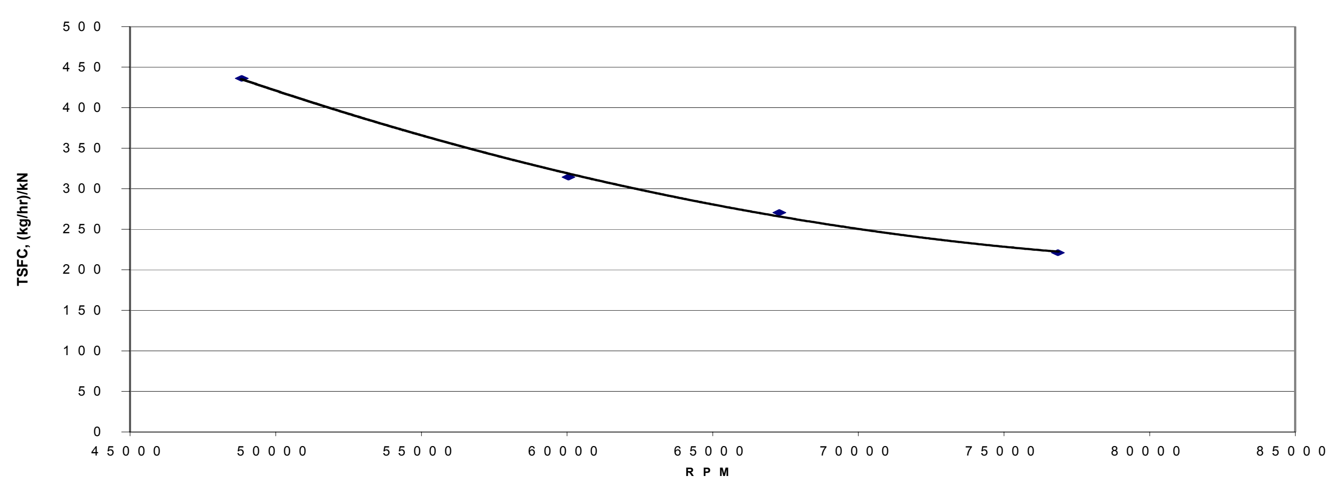


Figure 13: Thrust specific fuel consumption versus engine speed

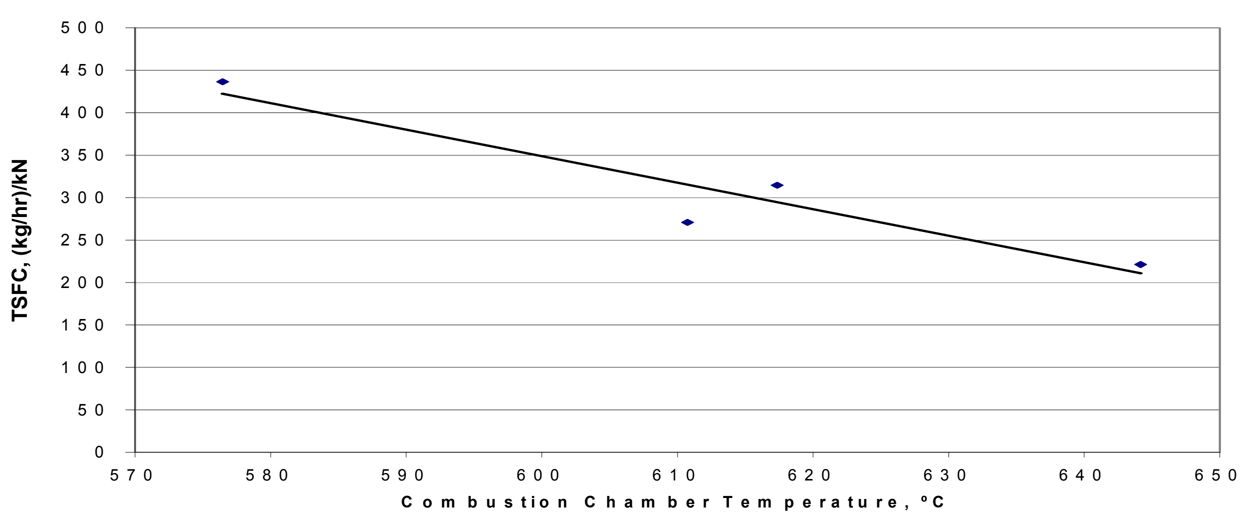


Figure 14: Thrust specific fuel consumption versus combustion chamber temperature

The Air/Fuel Ratio

Both air and fuel mass flow rates increase almost linearly as the jet engine speed increases (Figure 15). This nearly follows the "fan law" relating volumetric flow rate to speed. The air/fuel ratio varied in a narrow range as shown in Figure 16.

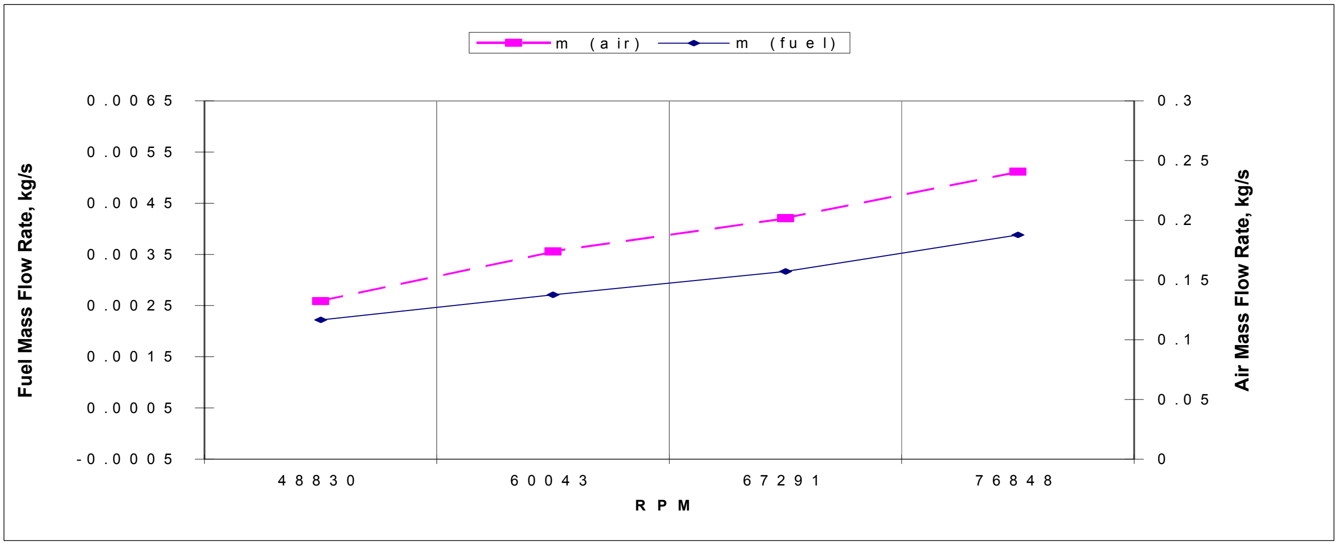


Figure 15: Mass flow rate of air and fuel versus engine speed

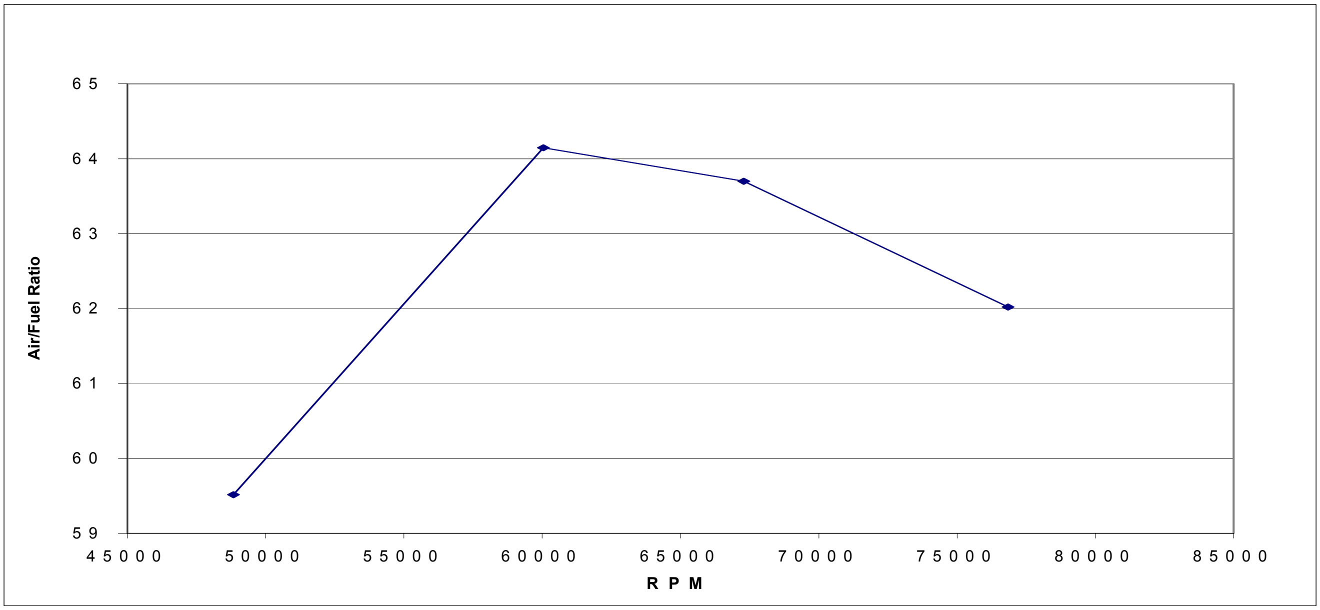


Figure 16: Air/Fuel ratio versus engine speed

Component Efficiencies

Figures 17-19 show the measured component efficiencies as functions of engine speed. As the engine speed was increased from 48,830 to 76,848 rpm, the compressor efficiency increased consistently and the turbine efficiency dropped by about 10%. The combustion chamber efficiency varied in the 70-80% range.

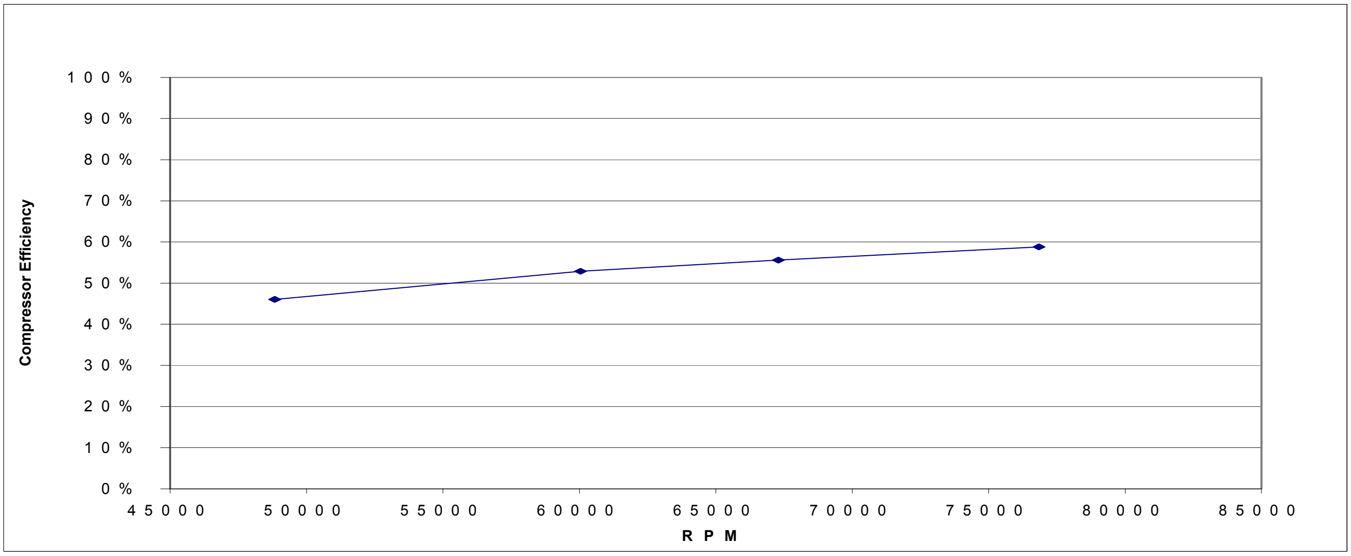


Figure 17: Compressor efficiency versus engine speed

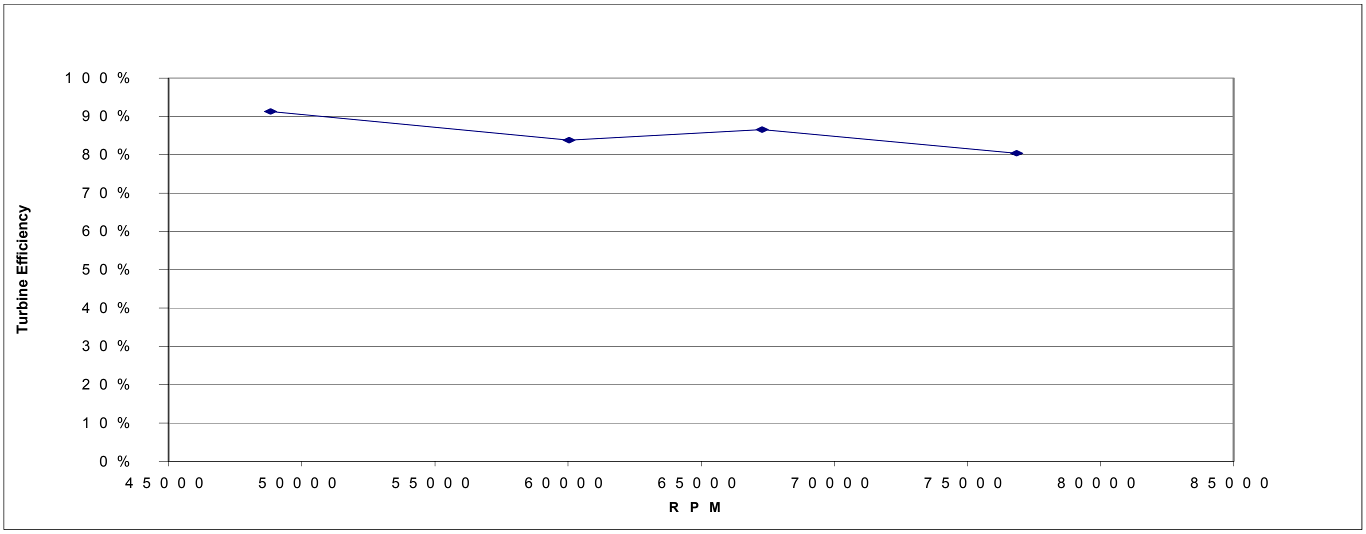


Figure 18: Turbine efficiency versus engine speed

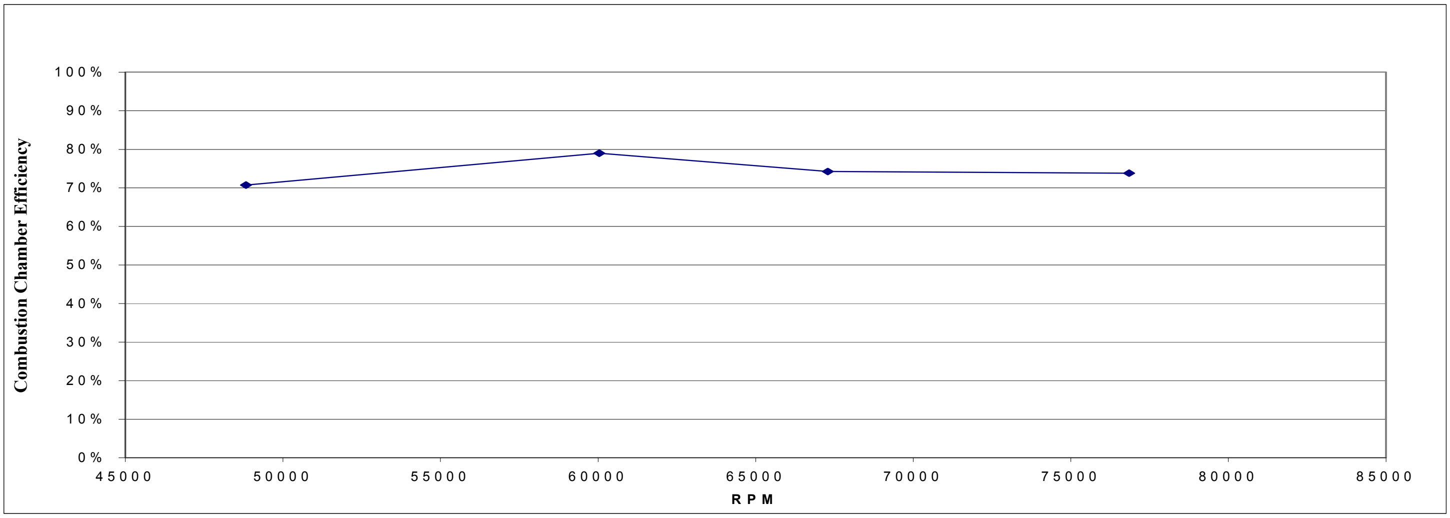


Figure 19: combustion chamber efficiency versus engine speed

Engine Emissions

Figures 20-23 show the measured THC, CO and NO_x emissions versus engine speed and turbine inlet temperature. As the engine speed and the combustion chamber outlet (turbine inlet) temperature increase, the THC in the exhaust gases decreases while the CO mission remains fairly constant. Higher combustion temperatures increase NO_x emissions considerably as expected.

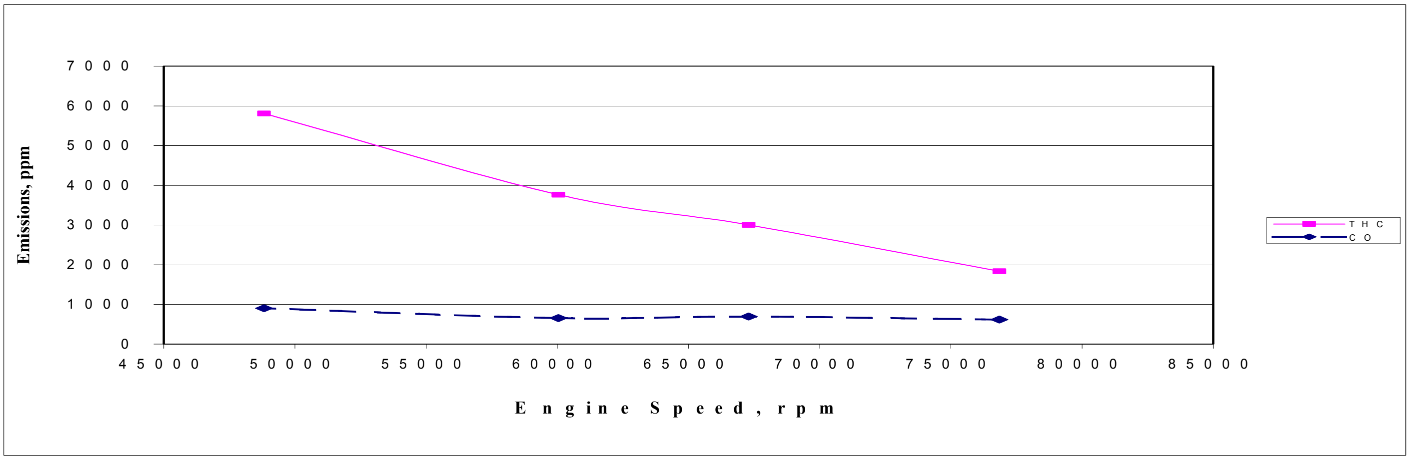


Figure 20: THC and CO emissions versus engine speed

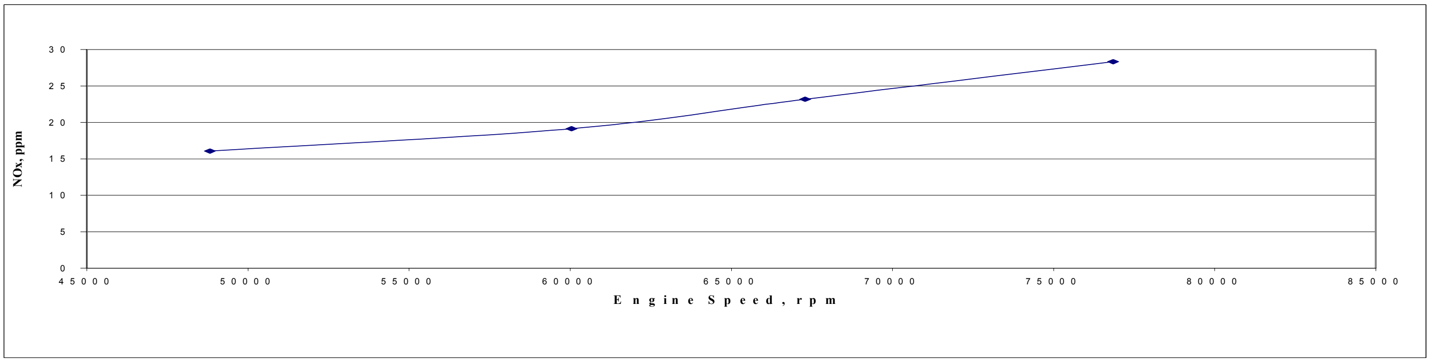


Figure 21: NOx emission versus engine speed

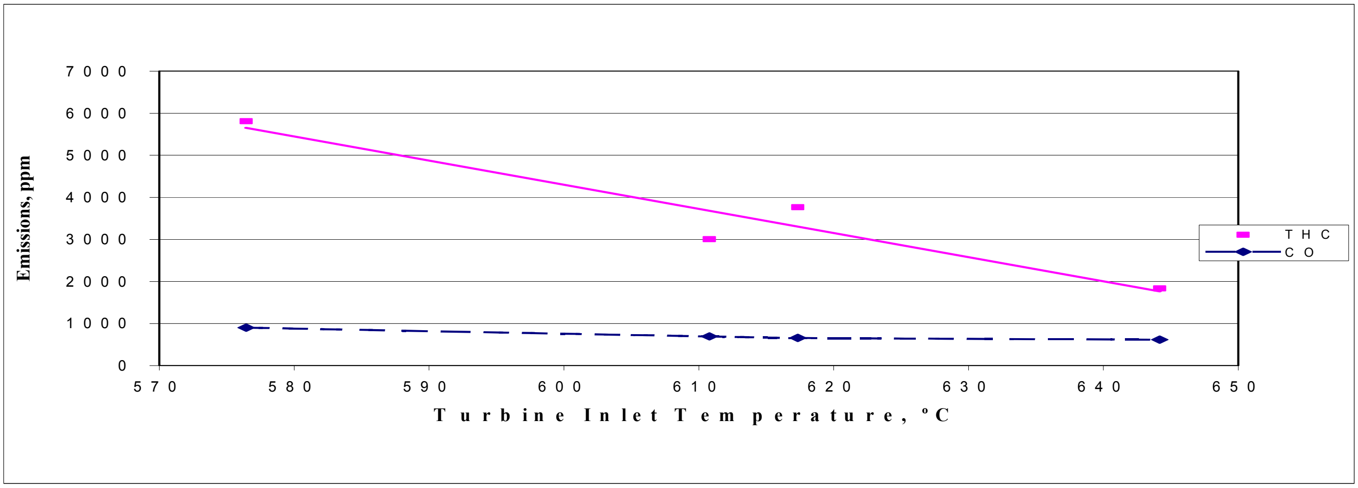


Figure 22: THC and CO emissions versus turbine inlet temperature

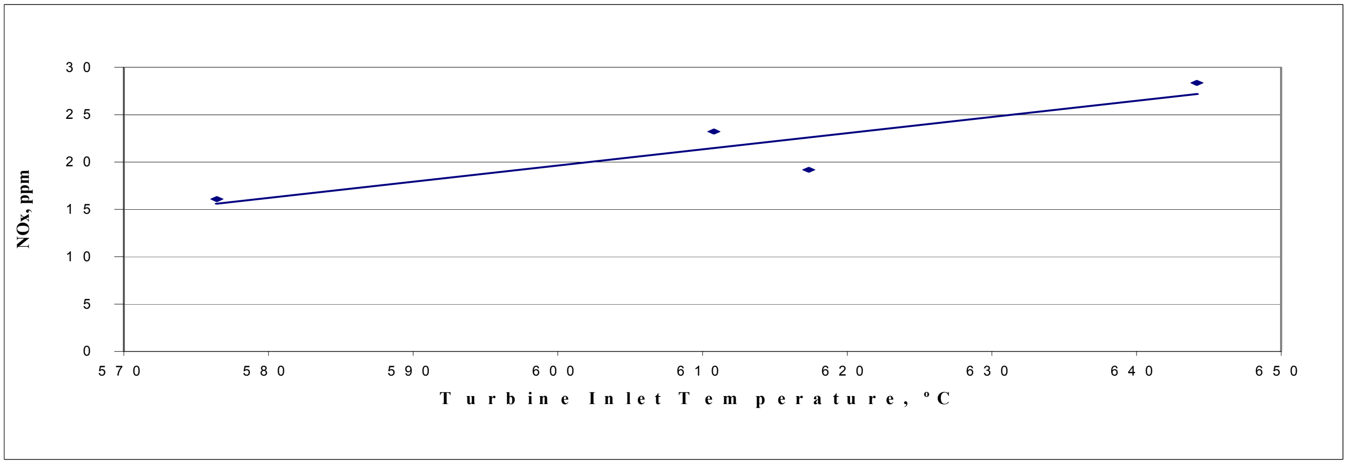


Figure 23: NOx emission versus turbine inlet temperature

Engine Energy Balance

As indicated by the energy balance pie chart shown in Figure 24, for the SR-30 turbojet engine tested on a stationary test stand, 68-70% of the heat released by the fuel leaves the engine as exhaust enthalpy and 1-4% as exhaust kinetic energy. The remainder (26-31%) represents heat loss to the room.

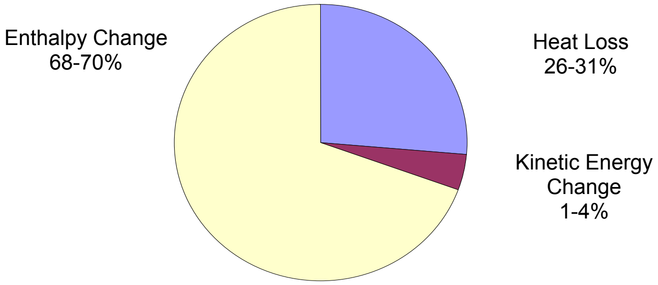


Figure 24: Energy Balance Pie Chart

Conclusions:

The SR-30 Turbojet engine has been successfully implemented at the Kettering University Energy Systems Laboratory. It has proven to be a valuable educational tool. The students enjoy operating this engine and refer to this experiment as the "most interesting experiment" in the laboratory. Experimental results obtained from this engine agree well with students' expectations and their calculated results. By combining the principles of thermodynamics, fluid mechanics and elementary combustion, this experiment has proven to be an integrated and exciting teaching tool.

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