

MAJOR PROJECT / DISSERTATION

LEVEL 6

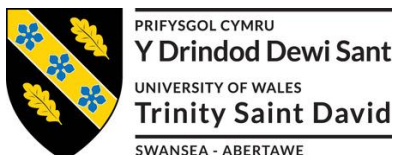
PRACTICAL STUDY OF THE KTM SX-F 450 ENGINE

ABSTRACT

The project is a practical study of the KTM SX-F 450, a 4-stroke single cylinder naturally aspirated engine, focusing on the intake system, the valve train measurement, the exhaust gas pulsation and data acquisition system. The intake system is tested using a comprehensive flow bench procedure with throttle body through the full range of butterfly position. The valve train measurement and calculations are identifying appropriate valve spring stiffness while using an own developed rig tool. The exhaust gas pulsation study required a top-dead-centre encoder and pressure-transducer calibration rig, both developed by myself. The data acquisition system does real time analysis on engine performance, integrates Air Mass Flow meter and Lambda sensor, measures exhaust gas temperatures and injector operations.

Besides the description of the experiment, this paper also holds the theoretical background, the boundaries, the Gantt chart and the costs involved of the study.

Átfogó, rgégen elkezdett project, ami tovább fog folytatódni, ami nem csak az egyetmi tanulmányok elfvégzése céljából készül. Mindenféle meglévő alkatrészek összevegyítésre, optimalizálása. Önmagában a disszertáció az engine felmérésével, feltérképezésével, alehetőségek kihasználásával foglalkozik és a data acquisition system felépítésével és felhasználásával foglalkozik. Maga a teszt nem része ennek a projektnek.



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1 Introduction

(A) The KTM SX-F 450 engine

My final year project is the practical study of a KTM 450cc 4-stroke single cylinder naturally aspirated engine, focusing on the intake system, the valve train measurement, the exhaust gas pulsation and data acquisition system. The intake system is tested using a comprehensive flow bench procedure with throttle body through the full range of butterfly position. The valve train measurement and calculations are identifying appropriate valve spring stiffness while using an own developed rig tool. The exhaust gas pulsation study required a top-dead-centre encoder and pressure-transducer calibration rig, both developed by myself. The data acquisition system does real time analysis on engine performance, integrates Air Mass Flow meter and Lambda sensor, measures exhaust gas temperatures and injector operations.

Ez a típusú motor engine, egy off roadra fejlesztett négysebességes erőmű, de a ktm családnak egy másik típusával, ami endurora, vagy supermoto versenyekre fejlsztett típusával össekombinálva egy roadracing engine fejlesztése a fő cél, a supermono 2.5. gyártva van 4 és 5 sebességes váltóval.

Ktm család másika EX-f 450 6 sebességes váltóval van fejlesztve, különböző áttételvariációkkal. Rengeteg opció van a különböző családtagok összeépítésében a verseny követelményeihez össze lehet rakni egy kitet. Primary áttétele offroadra van. Könnyen adaptálható 510 kobcentis több vezérműtengelyt is össze lehet rakni.ez a further work. A simsonnal is ez történt anno.

Önmagában a project többflek területet ölel fel önmagamot fejleszteni, gépmunka, fabrikáció, alkatrészfejlesztés, módosítása, szerszámok, test rígek legyártása, a atesztek leonoyolitása,a pico tanulmányozása, alkalmazásoknak utána járása, milyen rendszert tudok felépíteni, saját project saját budgetből. Elég széleskorú tanumányozást igényelt, sok munkaórát igényelt. Nem specializáltam a hegesztési munka elvégzéséig, a tervezést,a munkafolyamatok összeállítását, megcsinálni a tervet, ..

Ez egy élő design process amit a Orol Kellett felállítani a saját vzetésem alapján. Széles az egysz project szöükséglete. Sok területet olel fel.

2 Volumetric Efficiency, Thermal Efficiency, Engine Performance Development.

Mitől függ, hogy hatnak egymásra.

VE és exhasust pulse tuning együtt jár.

Feltérképezéséről szól a project.

EPT alapötlet, hogy a ... CVben össze van foglalva.

Encoding TDC az egyik.

Picoról lehet belerakni ilyen izéket.. ilyen .. de az alapelmélete a TDCnek az, hogy egy hall-effect sensor... azzal meghatározni a főtengely állás pozícióját, behatárolni az alsó és felső holtpontot, és ezt a signált felhasználni.

Pico automotive istennyilának az egyikfunkcióját használva erre a jelre fel lehet rakni egy koordinttarendszert is akkor az mutatja a teljes, 720fokos koornidnátarendszer, ami mutatja a teljes vertikális izékkell,, screenshot a fájlból, és azt leírni, hogy néz ez ki.

EPThez tartozik a pressure transducer beépítése a kipufogócsatornába (exhaust port).

Erre lett fejlesztve a pressure sensor calibration, a rig, ide jön egy foot vagy rajz, le kell írni az alapötletét, ahogy összeáll vagy működik.

Exhaust gas temperature measurement. EGTM. Pico tc-08 8 csatornás data logging systeme. 5 thermocap.

Mass air flow fitment/calibration.

Erről lehet egy csomót írni.

Szenzorok kalibrálása. Data acq sys. Mi a célja, mit tudna. Mindez azért, hogy a Vet tudja vizsgálni, meg a O₂ sensor

Initial dyno run. Problémák adódtak. A gép gyakorlatilag megállt, nem működött.

KTM user tool.. pontos név kell.

A lényeg a teszt lett volna, a motor finomhangolása.

Erről lehet írni egy keveset, még appendixbe beletenni ktm-es pdfből ábrákat.

Kell egy konklúzió és egy analízis.. rengeteg anyag...

Az elején az Otto motor működése. Ideal Otto cycle & p-v diagram.

Air mass flowhoz. Air box gyártás. Esztergálás. A folyamat leírása.

Rengeteg munkálatokból állt az egész project. Miből lett, hogy lett és mi a vége.

Introductionbe meg kell említeni, hogy miért az egész hogy a super mono kategóriában, blabla...

Az Excelt meg kell csinálni Zsoltnak.

Blair könyvből és a pár újságikkból kell összedetni. P-v diagram.

Le kell írni, a Picot hogy használjul.

Pumping loss.

3 Theoretical Background

(A) The Ideal Otto Cycle

i. Introduction

The **KTM FX-S 450** engine, like any other internal combustion engine, converts thermal energy into mechanical energy, forming a so-called **heat engine**. Where conversions take place between heat and other forms of energy in the system, thermodynamics concerns and the system is called a **thermodynamic system**. These systems can be described by the properties of their components such as heat, temperature, pressure, volume, density, entropy and phase at a given point in time. (Wu, 2004)

When heat energy is applied to change the state of a working fluid in order to be extracted in the form of mechanical work and then to return the working fluid into its initial state, the thermodynamic system is called a **thermodynamic cycle**. The processes of a 4-stroke internal-combustion spark-ignition engine is based upon the principles of a **theoretical constant volume cycle**, which is called as the **Otto cycle** today. (Lawson, 2018) (Bonnick, 2008)

(The principles of the cycle were patented by the French engineer Alphonse Beau de Rochas in 1862 and the first engine based upon this theory was built by **Nikolaus A. Otto**. Otto's development became an immediate success therefore the theory is named after him. (Bonnick, 2008) (Encyclopædia Britannica, 2018))

An idealized thermodynamic cycle describes the way how heat energy should be converted to turn pressure and volume changes into mechanical motion. Therefore, to represent the theory, the processes of the engine operating cycle are shown on a graph of pressure (p) and volume (V), referred as the **pV diagram**. (Lawson, 2018)

ii. Phases of the Otto Cycle

The **Otto cycle's pV diagram** builds up by a pair of quasi-parallel isentropic (frictionless, adiabatic and reversible) and a pair of parallel isochoric (constant volume) processes.

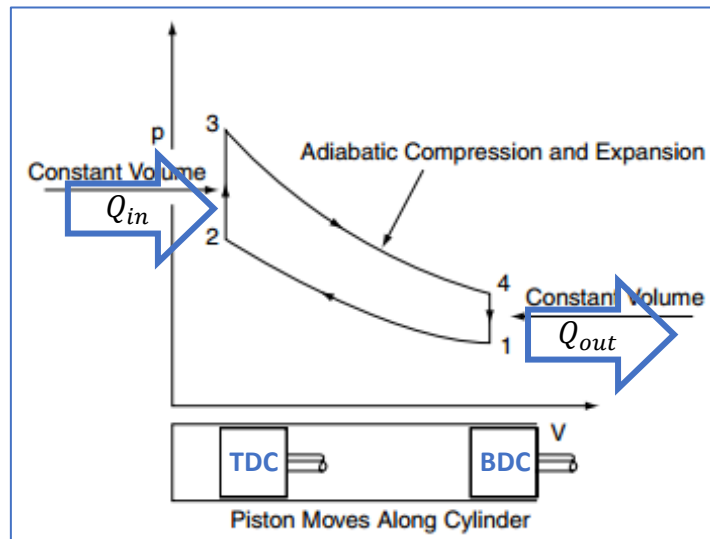


Figure 3.1 The pV diagram of the Otto cycle with the heat energies (Bonnick, 2008)

Figure 3.1 shows this indicator diagram of the ideal engine, marking the steps of the cycle by 1, 2, 3, and 4. The position of piston if it is either in Bottom Dead Centre (BDC) or Top Dead Centre (TDC), and the heat energy supplied (Q_{in}) to and rejected (Q_{out}) from the air are also shown on the picture.

- The **Intake Stroke (0-1)** lets the working fuel - a mass of gas (fuel-air mixture) - into the piston/cylinder by keeping the exhaust valve closed and closing the open intake valve at the end of the process.
 - This is an isobaric process: the engine takes cool oxygen-rich air in at constant pressure.
- The gas is adiabatically compressed in the cylinder by the piston during the **Compression Stroke (1-2)** when piston is pushed along from BDC to TDC.
 - This is the first isentropic phase of the cycle, an isentropic compression.
 - Hence, it is assumed, that no mechanical energy is lost due to friction and no additional or lost heat transferred between the gas and the cylinder and surroundings, leaving the process reversible.
 - Work is done by the piston when it decreases the volume of gas from V_1 to V_2 according to the *compression ratio* ($R = \frac{V_1}{V_2}$).
- In the following **Ignition or Combustion Phase (2-3)** the piston is at TDC and the injected fuel is combusting.

- This is considered as heat energy (Q_{in}) is added to the working gas while keeping the volume essentially constant ($V_2 = V_3$).
- The process is representing the ignition of the fuel-air mixture and the subsequent rapid burning.
- This is the first isochoric phase of the cycle.
- Therefore, no work is added to or removed from the system otherwise it would require the movement of the system boundaries.
- The pressure is rising from P_2 to P_3 corresponding to the *explosion ratio* ($\frac{P_3}{P_2}$).
- During the **Expansion or Power Stroke (3-4)** the high pressure (P_3) creates the force which pushes the piston towards BDC.
 - This is the second isentropic phase of the cycle, an isentropic expansion.
 - There is no heat transfer between the gas in the cylinder and its surroundings.
 - In this phase gas expands from V_3 to V_4 adiabatically doing work on the piston.
- In the **Idealized Heat Rejection or Exhaust Phase (4-1)** the piston is resting at BDC and a cold body is brought into contact with the cylinder head.
 - This process is removing the remaining energy of the gas in the cylinder (Q_{out}) at constant volume ($V_4 = V_1$) until pressure returns from P_4 to P_1 .
 - This is the second isochoric phase: the rejection of heat at constant volume.
 - No work is done on the system.
 - Gas returns into state 1 by the end of this phase.
- During the **Exhaust Stroke (1-0)** the exhaust valve is opened at Point 1 and piston is moving from BDC to TDC leaving the mass of air and waste heat to be vented to the atmosphere.
 - It is a constant pressure (isobaric) process.
 - The process starts anew.

This section is referenced from the following literacy: (Blair, 2007) (Bonnick, 2008) (Lawson, 2018) (Moran & Shapiro, 2006) (Wu, 2004).

iii. Thermodynamics of the Otto Cycle

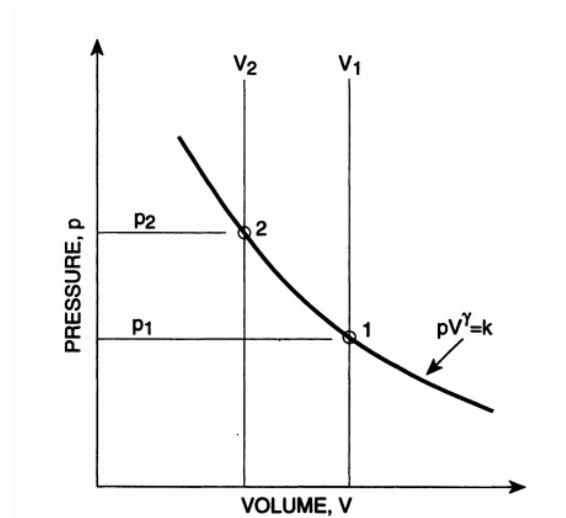


Figure 3.2 The pV changes for a closed system (Blair, 2007)

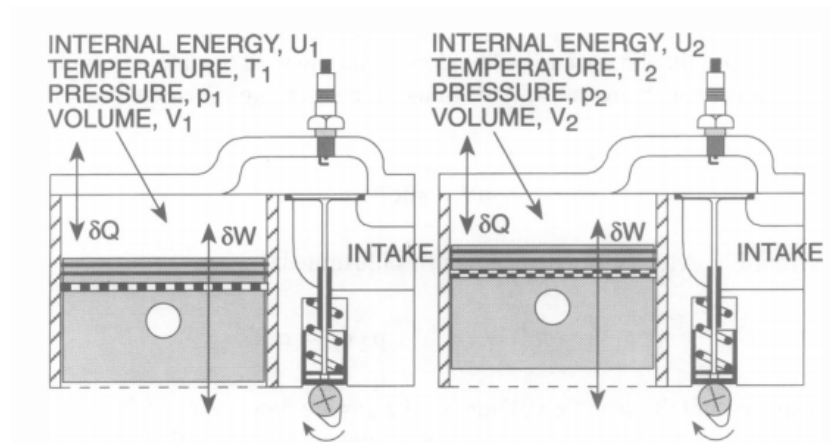


Figure 3.3 A closed system process in a four-stroke engine (Blair, 2007)

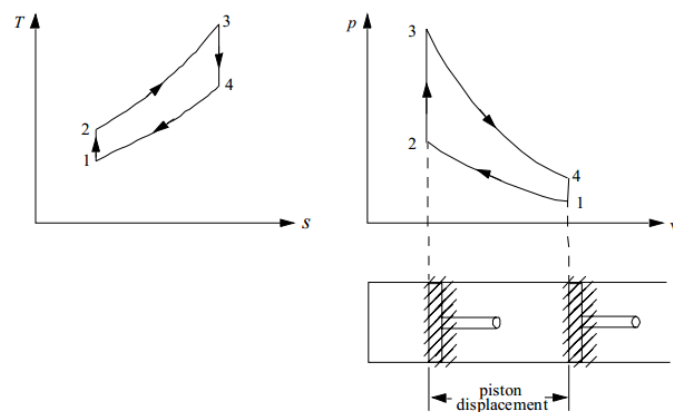


Figure 3.4 The Ts (Entropy) and pV diagrams of the Otto Cycle (Wu, 2004)

The Otto Cycle is a **closed system**, hence

- the pressure (p), volume (V), temperature (T) and enthalpy (h) may change,
- the **mass (m) stays constant** within the system. (Eq. 3.1)

The **first law of thermodynamics for a closed system** states that any **changes of heat transfer (δQ)** and internal energy (dU) are related to any possible work change (δW) by

$$\delta Q = dU + \delta W \quad (\text{Eq. 3.2})$$

Although (Eq. 3.9) would be more complete with change of kinetic (KE), potential (PE) or any unknown energy being added, only the change of internal energy (dU) is considered as real significance in a closed system, hence the others are assumed to be zero and left out from the equation.

The **usage of the differential terms δ and d** are mathematically reasoned.

- While heat (Q) and work (W) are so-called *path functions*, i.e. their outcome based on their path,
- until internal energy (U), which arises from molecular motion, is a so-called *point function*, i.e. its outcome depends only its initial and final states, but independent of path.

Signs are also important in this discussion.

- Heat is a positive quantity in general, although in the following thermodynamic equations it is signed
 - positive, when heat is transferred TO the system from the surroundings,
 - negative, when heat is transferred FROM the system to the surroundings.
- Work is also a positive quantity when it is done by the system, although, in the following equations it is signed
 - positive, when the system is doing work,
 - negative when work is being done on the system.

It also must be recognized, that the useful work done during the cycle is represented by the area enclosed by the pV diagram.

If the gas within a closed system experiences a work process (δW) it is observed by a change of volume (dV) at pressure p and can be evaluated as $\delta W = pdV$. (Blair, 2007)

For any adiabatic ($Q = 0$) processes the work done is a function of state.

Since the change of internal energy (dU) depends only on the change of state, it shows that work (W) is the function of the state change. (Spakovszky, 2008)

$$Q = 0 \quad (\text{Eq. 3.3})$$

$$dU = -W \quad (\text{Eq. 3.4})$$

$$Q = W \quad (\text{Eq. 3.5})$$

The first law of thermodynamics for a closed system also states that processes of a thermodynamic cycle can be evaluated directly as below. (Blair, 2007)

$$\oint \delta Q = \oint \delta W \quad (\text{Eq. 3.6})$$

which means, that $\oint dU = 0 \quad (\text{Eq. 3.7})$

According to *Figure 3.2 The pV changes for a closed system* (Blair, 2007),

the work done by the system is $W = p_2 V_2 - p_1 V_1 \quad (\text{Eq. 3.8})$

the internal energy change is $dU = U_2 - U_1 \quad (\text{Eq. 3.9})$

Substituting (Eq. 3.8) and (Eq. 3.9) into (Eq. 3.4) leads to the equation of enthalpies of the system, which says, that the initial and final states of the system has the same value of the quantity $U + pV$. This quantity is defined as **the enthalpy (H)**. (Spakovszky, 2008)

$$U_2 + p_2 V_2 = U_1 + p_1 V_1 \quad (\text{Eq. 3.10})$$

Which is equal to $H_2 = H_1 \quad (\text{Eq. 3.11})$

In other “words” $H = U + pV \quad (\text{Eq. 3.12})$

Substituting (Eq. 3.9) into (Eq. 3.2) leads to the following:

$$Q = (U_2 - U_1) + (p_2 V_2 - p_1 V_1) \quad (\text{Eq. 3.13})$$

$$Q = (U_2 + p_2 V_2) - (U_1 + p_1 V_1) \quad (\text{Eq. 3.14})$$

$$Q = H_2 - H_1 \quad (\text{Eq. 3.15})$$

Differentiating the definition of work (Eq. 3.8) and enthalpy (Eq. 3.12) we get

$$\delta W = p dV \quad (\text{Eq. 3.16})$$

$$dH = U + pdV + Vdp \quad (\text{Eq. 3.17})$$

Substituting (Eq. 3.17) into (Eq. 3.2) then reorganizing leads to the following equation:

$$dH = \delta Q - \delta W + pdV + Vdp \quad (\text{Eq. 3.18})$$

Which is equal to $dH = \delta Q + Vdp \quad (\text{Eq. 3.19})$

The gas species that make up the working fluids in internal combustion engines can usually be treated as ideal gases. Therefore, **the ideal gas law** – or General Gas Equation in other words – can be applied to get **the equation of thermodynamic state** of the system:

$$pV = mRT \quad (\text{Eq. 3.20})$$

Where p is the pressure, V is the volume, m is the mass, R is the specific gas constant, and T is the absolute temperature of the gas, and all units are strict SI units, such as Pascals (Pa) for pressure, cubic meters (m^3) for volume, kilograms (kg) for mass, Joules per mole Kelvin ($J/molK$) and Kelvins ($^{\circ}K$).

If the system is experiencing any change in pV , it does result a change in mRT , therefore

$$d(pV) = d(mRT) \quad (\text{Eq. 3.21})$$

When pressure is constant, and because mass (m) and specific gas constant ($\bar{R}$) is unchanged, this equals to

$$pdV = mRdT \quad (\text{Eq. 3.22})$$

Properties of the system are describing its state. There are so-called **intensive properties** of the working fluid which are independent (eof the size of the system. These can be developed on a per unit mass basis from the so-called **extensive**, system-size dependent properties.

Specific heat transfer	δq	$= \frac{\delta Q}{m}$	(Eq. 3.23)
------------------------	------------	------------------------	------------

Specific internal energy	du	$= \frac{dU}{m}$	(Eq. 3.24)
--------------------------	------	------------------	------------

Specific work transfer	δw	$= \frac{\delta W}{m}$	(Eq. 3.25)
------------------------	------------	------------------------	------------

Specific enthalpy	dh	$= \frac{dH}{m}$	(Eq. 3.26)
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Specific volume	v	$= \frac{V}{m}$	(Eq. 3.27)
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Specific gas constant	R	$= \frac{\bar{R}}{m}$	(Eq. 3.28)
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Substituting (Eq. 3.23-25) into (Eq.3.2) results a **specific formulation of the first law of thermodynamics**:

$$\delta q = du + \delta w \quad (\text{Eq. 3.29})$$

Substituting (Eq. 3.16) and (Eq. 3.29) into (Eq. 3.19) results a **specific formulation of enthalpy**:

$$dh = du + pdv + vdp \quad (\text{Eq. 3.30})$$

By introducing the definition of **density (ρ)**, measured in kg/m^3 ,

$$\rho = \frac{m}{V} \quad (\text{Eq. 3.31})$$

which is the reciprocal of the specific volume

$$\rho = \frac{1}{v} \quad (\text{Eq. 3.32})$$

it can be shown, that

$$pV = mRT$$

is equal to

$$pV = \rho RT \quad (\text{Eq. 3.33})$$

and leads to

$$pv = RT \quad (\text{Eq. 3.34})$$

Further intensive property is the **specific heat capacity**, which describes the relations between heat and temperature changes of the system. (Blair, 2007)

Specific heat capacity	c	$= \frac{c}{m}$	(Eq. 3.35)
------------------------	-----	-----------------	------------

By definition it is

$$c = \frac{\delta q}{dT} \quad (\text{Eq. 3.36})$$

Which is equal to

$$C = \frac{\delta Q}{dT} \quad (\text{Eq. 3.37})$$

Taking the definition further and considering circumstances, there are two specific heats to be noted:

c at constant volume	c_V	$= \frac{du}{dT}$	(Eq. 3.38)
------------------------	-------	-------------------	------------

c at constant pressure	c_P	$= \frac{dh}{dT}$	(Eq. 3.39)
--------------------------	-------	-------------------	------------

Based on the definition of enthalpy, (Eq. 3.39) can be written as:

$$c_P = \frac{d(u+pv)}{dT} \quad (\text{Eq. 3.40})$$

Rearranging (Eq. 3.38) and (Eq. 3.39) it brings the following equations:

$$du = c_V dT \quad (\text{Eq. 3.41})$$

$$dh = c_P dT \quad (\text{Eq. 3.42})$$

Rearranging (Eq. 3.23-25) leads to the following:

$$c_P dT = d(u + pv)$$

$$c_P dT = du + d(pv)$$

$$c_P dT = c_V dT + d(RT)$$

$$c_P dT = c_V dT + R dT$$

$$c_P = c_V + R \quad (\text{Eq. 3.43})$$

Which is equal to

$$c_P - c_V = R \quad (\text{Eq. 3.44})$$

In this relation of the specific heats and gas constant (Eq. 3.41) the units depend on the mass considered for **a unit mass of gas**. For **one kmol of gas** the expression is changing slightly as the following, where $\bar{R}$ is the universal gas constant. (Spakovszky, 2008)

$$C_P - C_V = \bar{R} \quad (\text{Eq. 3.45})$$

The **specific heat ratio** is also must be noted here. For ideal gases it can be considered as a constant factor in adiabatic engine processes. It is a function of temperature (T) only.

$$\gamma = \frac{c_P}{c_V} \quad (\text{Eq. 3.46})$$

This is equal to

$$\gamma = \frac{C_P}{C_V} \quad (\text{Eq. 3.47})$$

Rearranging (Eq. 3.30) and (Eq. 3.32) it comes out, that

$$\gamma = 1 + \frac{R}{c_V} \quad (\text{Eq. 3.48})$$

Which is equal to

$$\gamma - 1 = \frac{R}{c_V} \quad (\text{Eq. 3.49})$$

The adiabatic constant is determining **the speed of sound** in ideal gases also. (Georgia State University, 2005)

The adiabatic process means, that (Eq. 3.3) $Q = 0$

The

The ideal gas law (Eq. 3.20) states, that $pV = mRT$

Definition of specific heat (Eq. 3.41) shows, that $du = c_v dT$

Definition of enthalpy (Eq. 3.4) shows, that $dh = du + p dv + v dp$

Substituting (Eq. 3.12) into (Eq. 3.5), it brings to the follows:

$$\delta Q = mC_v dT + m\bar{R}dT \quad (\text{Eq. 3.50})$$

$$\text{Which is equal to} \quad \delta Q = m(C_v + \bar{R})dT \quad (\text{Eq. 3.51})$$

$$\text{Taking (Eq. 3.4) in:} \quad \delta Q = mC_p dT$$

$$\text{Leads to the equation} \quad C_p = C_v + \bar{R} \quad (\text{Eq. 3.52})$$

During a complete cycle the gas returns to its original state of temperature, pressure and volume, hence the **net internal energy change (ΔE)** of the system is zero. This means that all heat or work energy added to the system (E_{in}) must be offset by all heat or work energy that leaves (E_{out}) it. Marking the entering energy as positive and the leaving one as negative, the following can be stated:

$$\Delta E = E_{in} - E_{out} = 0 \quad (\text{Eq. 3.53})$$

Reversible, adiabatic processes for an ideal gas

If the gas within a closed system experiences a work process (δW) it is observed by a change of volume (dV) at pressure p and can be evaluated as

$$\delta W = p dV \quad (\text{Eq. 3.54})$$

The internal energy (dU) can be evaluated for any given process by

$$dU = m C_V dT \quad (\text{Eq. 3.55})$$

where C_V is the specific heat at constant volume (Blair, 2007).

Substituting (Eq. 3.3-4) into (Eq. 3.2) results the general statement of the first law of thermodynamics:

$$\delta Q = m C_V dT + p dV \quad (\text{Eq. 3.56})$$

In other words, the total of heat energy equals to the sum of the energies

$m C_V dT$, which is increasing temperature

$p dV$, which is doing work.

From Figure 3. , where temperature changes from T_1 to T_2 , the internal energy change can be calculated as follows:

$$U_2 - U_1 = \int_{T_1}^{T_2} m C_V dT \quad (\text{Eq. 3.57})$$

Considering the specific heat term as constant:

$$U_2 - U_1 = m C_V \int_{T_1}^{T_2} dT$$

$$U_2 - U_1 = m C_V (T_2 - T_1) \quad (\text{Eq. 3.58})$$

The following equations can be stated here:

$$\int_1^2 \delta Q = Q_1^2 \quad (\text{Eq. 3.59})$$

$$\int_1^2 \delta W = \int_1^2 p dV = W_1^2 \quad (\text{Eq. 3.60})$$

$$\int_1^2 dU = m C_V (T_2 - T_1) \quad (\text{Eq. 3.61})$$

As the only work is done on the system (working fuel) is the heat transfer, (Eq. 3.1) is equal to:

$$W = Q_{in} - Q_{out} = 0 \quad (\text{Eq. 3.62})$$

The **thermal efficiency (η)** is defined as the following:

$$\eta = \frac{\text{net work output}}{\text{heat input}} = \frac{W}{Q_{in}} = \frac{Q_{in} - Q_{out}}{Q_{in}} = 1 - \frac{Q_{out}}{Q_{in}} \quad (\text{Eq. 3.63})$$

If air is assumed to be the working fluid with constant specific heats, (Eq. 3.3) can be reduced to:

$$\eta = 1 - \frac{T_4 - T_1}{T_3 - T_2} \quad (\text{Eq. 3.64})$$

This section is referenced from the following literacy: (Blair, 2007) (Bonnick, 2008) (Lawson, 2018) (Moran & Shapiro, 2006) (Wu, 2004) (Heywood, 1988) (Spakovszky, 2008).

4 Cylinder head development

(A) Valve train measurement

Moment of inertia. Ez egy kulcskérdés, meg kell csinálni az excelt. Itt lehet használni matematikát meg képeket.

(B) Flow bench test

(C) Compression ratio measurement, correction and evaluation

5 Data acquisition system

Felépítése, célja, mit tartalmaz.

Eredeti elgondolás, exhaust pulse tuning volt a fő irányvonal, az exhaust irány. Erre lett az első

(A) Air mass flow meter, lambda sensor

Exhaust gas temperature measurement

6 Appendix

(A) Gantt Chart

(B) Costs

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