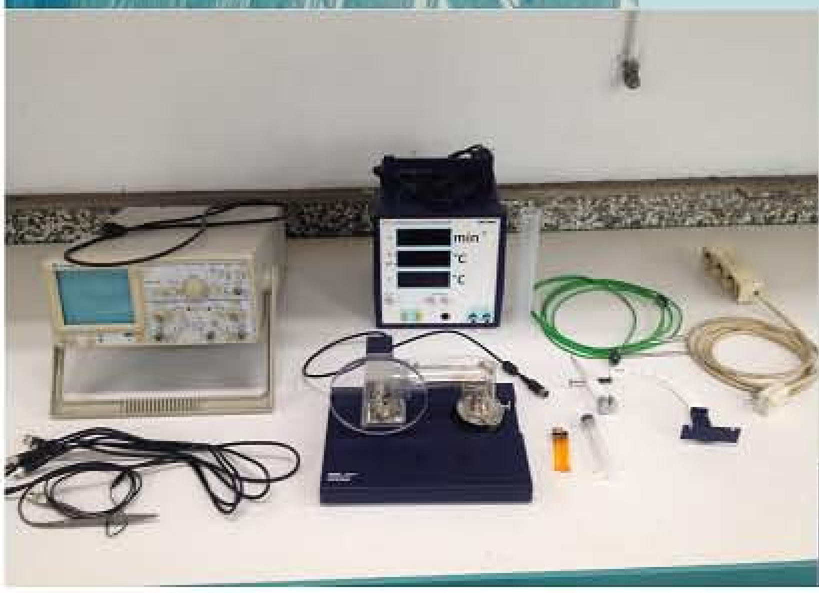
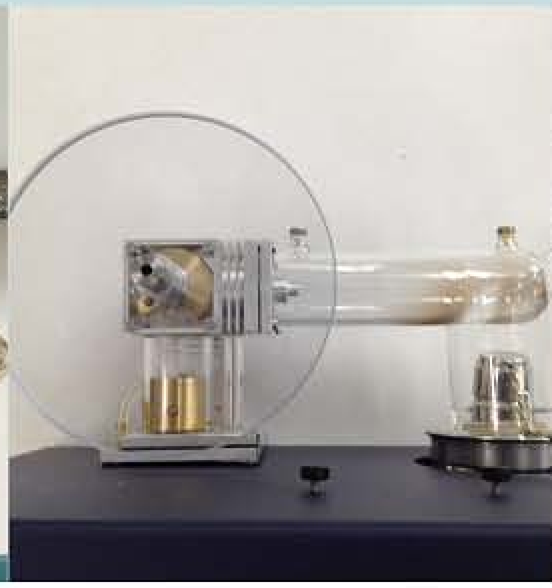
Thermodynamic Experiments

Stirling Engine

Experiment 5





儀器名稱	實驗前	實驗後
Stirling engine ×1		
Torque meter ×1		
Chimney for stirling engine ×1		
Meter f. stirling engine, pVnT ×1		
Sensor unit pVn for stirl. eng. ×1		
Syringe ×1		
Screened cable ×2		
Oscilloscope ×1		
Thermocouple ×2		
Graduated cylinder ×1		
Raw alcohol		

Principle

The Stirling engine is submitted to a load by means of an adjustable torque meter. Rotation frequency and temperature changes of the Stirling engine are observed. Effective mechanical energy and power are assessed as a function of rotation frequency. The amount of energy converted to work per cycle can be determined with the assistance of the PV diagram. The efficiency of the Stirling engine can be estimated.

Equipment

Stirling engine, transparent
Torque meter

Chimney for stirling engine
Meter f. stirling engine, $pVnT$
Sensor unit pVn for stirl. eng.
Syringe 20ml
Screened cable
Oscilloscope
Thermocouple NiCr-Ni, sheathed
Graduated cylinder, 50 ml, plastic
Raw alcohol for burning

Tasks

1. Determination of the burner's thermal efficiency
2. Calibration of the sensor unit
3. Calculation of the total energy produced by the engine through determination of the cycle area on the oscilloscope screen, using transparent paper and coordinate paper.
4. Assessment of the mechanical work per revolution, and calculation of the mechanical power output as a function of the rotation frequency, with the assistance of the torque meter.
5. Efficiency assessment.

Set-up and procedure

Experimental set up should be carried out as shown in Fig. 1. The base plate (mounting plate) of the Stirling engine must be removed, so that the latter can be fixed on the corresponding mounting plate of the pVn sensor unit. The incremental transmitter of the pVn sensor unit is firmly connected to the axle of the Stirling engine. The latter is then fixed upon the large base plate.

Before switching on the pVnT meter, make sure it is connected to the pVn sensor. Connect the p and V exits respectively to the Y and X oscilloscope channels.
After having been switched on, the pVnT meter display shows “cal”. Both thermocouples must now be set to the same temperature, and the “Calibration T” button depressed. This calibration of the temperature sensors merely influences the temperature difference display, not the absolute temperature display.

The upper display now shows “OT”, which means “upper dead centre point”. At this point, the engine is at its minimum volume. Now bring the working piston down to its lowest position by turning the engine axle, and press the “calibration V” button. Wrong calibration will cause a phase shift in the volume output voltage, and thus lead to a distortion of the pV diagram. The three displays should now be on, showing 0 revs/min, and the actual temperatures for T_1 and T_2.

1. **Thermal output of the burner**

   The amount of alcohol in the burner is measured before and after the experiment with a measuring glass (or a scale). The corresponding duration of the experiment is recorded with a watch or clock.

2. **Calibration of the pressure sensor**

   The pressure sensor must be calibrated so that the pV diagram can be evaluated quantitatively. This is carried out by means of a gas syringe.
   The flexible tube is removed from the mounting plate, and the voltage corresponding to atmospheric pressure p_0 is determined with the oscilloscope. The latter should be operated in DC and Yt mode, with calibrated Y scale. The piston of the airtight gas syringe is drawn out (e.g. up to 15 or 20 ml), and the syringe is connected to the flexible tube. The pressure (voltage) display on the oscilloscope screen is varied through isothermal increase and decrease of the syringe volume. The actual pressure inside the syringe can be calculated.

3. **Presentation and drawing of the *pV* diagram**

   The oscilloscope is now operated in the XY mode, with calibrated scales. Place the lighted burner below the glass cylinder, and observe the temperature display. When the temperature difference has reached approximately 80 K, give the flywheel a slight clockwise push to start the engine. After a short time, it should reach approximately 900 revs/min, and a Stirling cycle ought to show on the oscilloscope screen.

Before carrying out measurements of any kind, wait until temperatures T_1 and T_2, as well as the rotation frequency, are approximately constant. The lower temperature should now be about 70°C.

Rotation frequency and temperatures are recorded. Voltages corresponding to maximum and minimum pressures are read from the oscilloscope. The pV diagram is copied from the oscilloscope to a sheet of transparent paper. Make sure to look perpendicularly onto the screen when doing this. The Y axis ground line is drawn, too. Transfer the diagram to coordinate paper, in order to be able to determine the diagram surface.

4. Effective mechanical energy

In order to load the engine with a determined torque, the scale of the torque meter is fixed on the large base plate, and the inner metallic piece of the pointer is fixed on the axis before the flywheel. Friction between the pointer and the set-on metallic piece can be varied by means of the adjusting screw on the pointer. Adjustment must be done carefully, to make sure that the pointer will not begin to oscillate.

Start carrying out measurements with a low torque. After each adjustment, wait until torque, rotation frequency and temperatures remain constant. All values and the pV diagram are recorded.

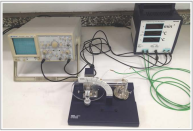
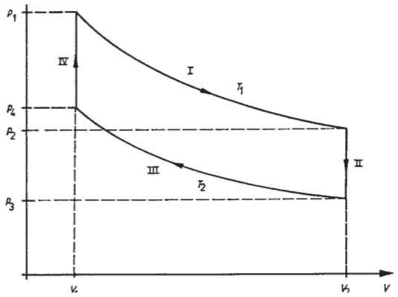


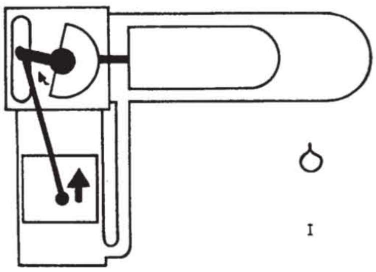
Fig. 1



Theory and evaluation

In 1816, Robert Stirling was granted a patent for a hot air engine, which is known today as the Stirling engine. In our times, the Stirling engine is used to study the principle of thermal engines because in this case the conversion process of thermal energy to mechanical energy is particularly clear and relatively easy to understand.

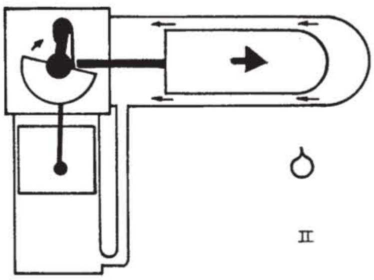
At present, the Stirling engine is undergoing a new phase of further development due to its many advantages.
Thus, for example, it constitutes a closed system, it runs very smoothly, and it can be operated with many different heat sources, which allows to take environmental aspects into consideration, too.



Theoretically, there are four phases during each engine cycle (see. Fig. 3a and 3b):

i. An isothermal modification when heat is supplied and work produced

$$V_1 \rightarrow V_2 \quad p_1 \rightarrow p_2 \quad T_1 = const.$$

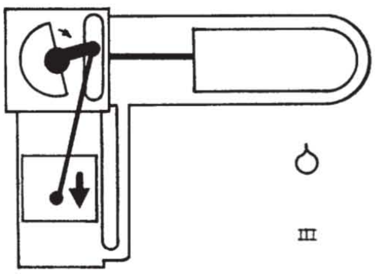


ii. An isochoric modification when the gas is cooled:

$$T_1 \rightarrow T_2 \quad p_2 \rightarrow p_3 \quad V_2 = const.$$

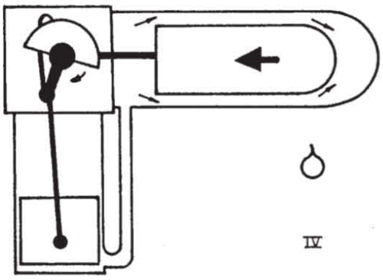
iii. An isothermal modification when heat is produced and work supplied:

$$V_2 \rightarrow V_1 \quad p_3 \rightarrow p_4 \quad T_2 = const.$$



iv. An isochoric modification when heat is supplied to the system:

$$T_2 \rightarrow T_1 \quad p_4 \rightarrow p_1 \quad V_1 = const.$$



According to the first law of thermodynamics, when thermal energy is supplied to an isolated system, its amount is equal to the sum of the internal energy in- crease of the system and the mechanical work supplied by the latter:

$$dQ = dU + pdV$$

It is important for the Stirling cycle that the thermal energy produced during the isochoric cooling phase be stored until it can be used again during the isochoric heating phase (regeneration principle).

Thus, during phase IV the amount of thermal energy released during phase II is regeneratively absorbed. This means that only an exchange of thermal energy takes place within the engine. Mechanical work is merely supplied during phases I and III. Due to the fact that internal energy is not modified during isothermal processes, work performed during these phases is respectively equal to the absorbed or released thermal energy.

Since $$pV=nRT$$

Where n is the number of moles contained in the system, and R the general gas constant, the amount of work produced during phase I is:

$$Q_H=W_1=\int_{V_1}^{V_2} pdV=nRT_1\int_{V_1}^{V_2}\frac{dV}{V}=nRT_1 ln\left(\frac{V_2}{V_1}\right)$$

Consequently, the amount of work supplied during phase III is

$$Q_c=W_3=\int_{V_2}^{V_1} pdV=nRT_2\int_{V_2}^{V_1}\frac{dV}{V}=nRT_2 ln\left(\frac{V_1}{V_2}\right)$$

$$W_1>|W_3| \qquad \textit{because} \qquad T_1>T_2$$

The total amount of work is thus given by the sum of W_1 and W_3. This is equal to the area of the pV diagram:

$$W_t=W_1+W_3$$

$$W_t=nRT_1 ln\left(\frac{V_2}{V_1}\right)+nRT_2 ln\left(\frac{V_1}{V_2}\right)$$

$$=nRT_1 ln\left(\frac{V_2}{V_1}\right)-nRT_2 ln\left(\frac{V_2}{V_1}\right)$$

$$=nR(T_1-T_2)ln\left(\frac{V_2}{V_1}\right)$$

Only part of this total effective energy W_t can be used as effective work W_m through exterior loads applied to the engine. The rest contains losses within the Stirling engine.

The maximum thermal efficiency of a reversible process within a thermal engine is equal to the ratio between the total amount of work $|W_1|$ and the amount of supplied thermal energy

$$Q_H = W_1$$

$$\eta_{th} = \frac{W_t}{W_1} = \frac{nR\left(T_1 - T_2\right) \ln\left(\frac{V_2}{V_1}\right)}{nRT_1 \ln\left(\frac{V_2}{V_1}\right)} = \frac{T_1 - T_2}{T_1}$$

Carnot found this to be the maximum thermal efficiency for any thermal engine, which can only be reached theoretically. One sees that efficiency increases with increasing temperature differences.

1. **Thermal output of the burner**

Duration	$\Delta t = 60$ min
Amount of alcohol burned	$\Delta V = 29$ ml
Alcohol density	$\rho = 0.83$ g/ml
Specific thermal power	$h = 25$ kJ/g

This allows to determine the mass of alcohol burnt per second:

$$\frac{\Delta m}{\Delta T} = 6.69 \times 10^{-3} \; \frac{g}{s}$$

as well as the thermal power of the burner:

$P_H = 167$ W.

2. **Calibration of the pressure sensor**

The pressure sensor measures the relative pressure as compared to the atmospheric pressure p_0. The volume modification of the gas syringe allows to calculate the modification of pressure, assuming that the change of state is isothermal, with pV = const.

At the initial volume V_0, pressure is equal to the atmospheric pressure p_0 Table 1-a shows an example of measurement for which p_0 was assumed to be normal atmospheric pressure (1013 hPa). The volume of the small flexible connecting tube (0.2 ml) can be considered to be negligible.

Table 1-a (example)

Compression				Expansion			
$\frac{V}{ml}$	$\frac{p}{hPa}$	$\frac{p-p_0}{hPa}$	$\frac{U}{V}$	$\frac{V}{ml}$	$\frac{p}{hPa}$	$\frac{p-p_0}{hPa}$	$\frac{U}{V}$
20	1013	0	2.35	15	1013	0	2.35
19	1066	53	2.51	16	950	-63	2.15
18	1126	113	2.71	17	894	-119	1.99
17	1192	179	2.89	18	844	-169	1.85
16	1266	253	3.10	19	800	-213	1.71
15	1351	338	3.40	20	760	-253	1.59

Table 1-b

Compression				Expansion			
$\frac{V}{ml}$	$\frac{p}{hPa}$	$\frac{p-p_0}{hPa}$	$\frac{U}{V}$	$\frac{V}{ml}$	$\frac{p}{hPa}$	$\frac{p-p_0}{hPa}$	$\frac{U}{V}$
20				15			
19				16			
18				17			
17				18			
16				19			
15				20			

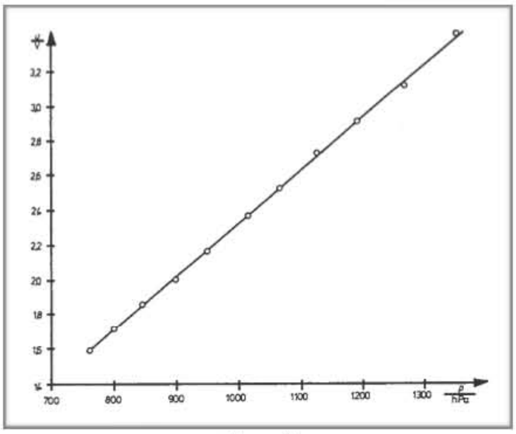


Fig. 4

Fig. 4 (example) shows the output voltage of the pressure sensor as a function of pressure. The slope of the regression line is:

$$\frac{\Delta U}{\Delta p}=3.04\times10^{-3}\left(\frac{V}{hPa}\right)\text{— example}$$

The voltage corresponding to atmospheric pressure p_0 is 2.35 V

Fig. 4: Characteristic curve of the pressure sensor. (example)

3. *pV* **diagram surface**

The oscilloscope's X measuring range is of 0.5 V/div. The *pVnT* measuring device displays the following voltages for the Stirling engine volumes (V_{min}, V_{max} are equipment constants):

$$V_{min} = 32cm^3 \rightarrow U_{min} = 0V$$
$$V_{max} = 44cm^3 \rightarrow U_{max} = 5V$$
$$\Delta V = 12cm^3 \rightarrow \Delta U = 5V$$

Thus, the scale factor for the X axis is 2.4 cm^3/V

With the used pressure sensor, the oscilloscope's Y measuring range was 0.2 V/div (with other pressure sensors it may be 0.5 V/div). Based upon the pressure calibration of Fig. 4, one finds a scale factor of 329 hPa/V or respectively 66 hPa/div for the Y axis.

Reading the voltages for maximum and minimum pressures with the oscilloscope being operated in the DC mode, the pressure values for the pV diagram can also be expressed in Pascal.

4. **Effective mechanical energy and power**

Effective mechanical energy during a cycle is calculated with the assistance of the torque M displayed by the torque meter:

$$W_m = 2\pi M$$

The displayed rotation speed n (revolutions per minute) is converted to the frequency f (revolutions per second). This allows to determine the mechanical power:

$$P_m = W_m f$$

Table 2 contains measured and calculated values. Fig. 6 displays the total effective energy W_{pV} assessed on the base of the pV diagram, effective mechanical energy W_m as well as friction energy per cycle W_{fr}, as a function of rotation frequency.

$$W_{fr} = W_{pv} - W_m$$

Table 2

M	n	T1	T2	Wm	*f*	Pm	Wpv	Wfr
$10^{-3}NM$	1/min	°C	°C	mJ	Hz	mW	mJ	mJ
0								
2.5								
4.0								
6.5								
8.2								
10.5								
12.2								
14.0								
15.0								
16.8								
18.3								
19.5								
22.0								
22.4								

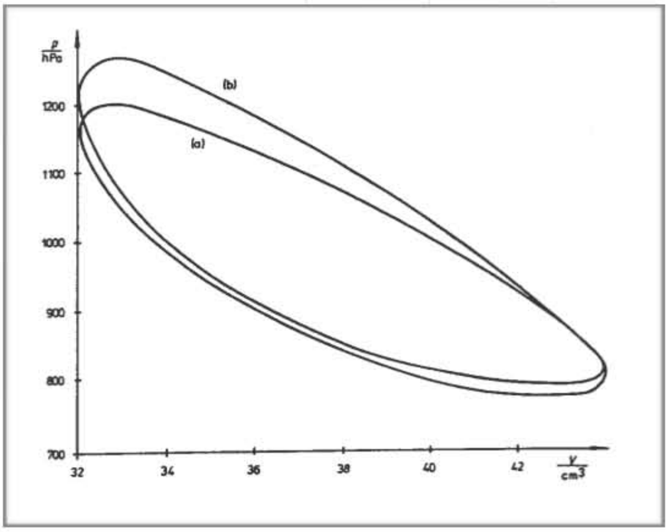
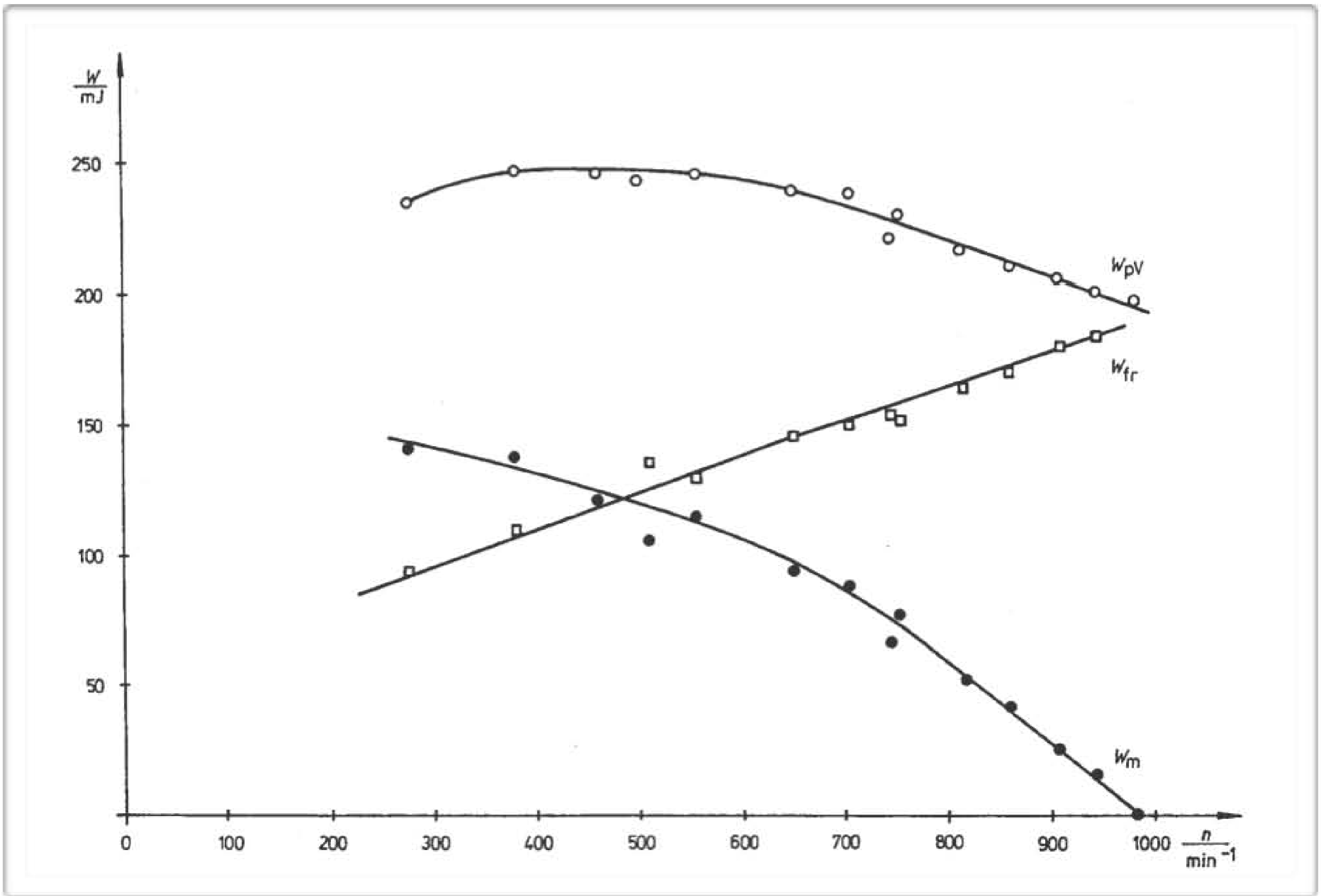


Fig. 5

Rotation frequency reaches its maximum value engine is not submitted to exterior loads (here: 982 min^{-1}). It is a function of thermal input and friction; in general its values lie within the range 800...1000 min^{-1}. Rotation frequency decreases with increasing exterior loads, until the Stirling engine stops (in general between 150...300 min^{-1}). Temperature T_1 increases strongly with decreasing rotation frequencies; T_2 decreases a little due to the fact that the air in the regenerator (that is on the wall of the displacing piston) is pre heated or respectively cooled to a better extent when rotation frequency is low. Pressure within the Stirling engine also varies with temperatures. This is clearly visible on the pV diagram (see Fig. 5).



W
mJ
250
200
150
100
50
0
100
200
300
400
500
600
700
800
900
1000
n
min⁻¹
W_pV
W_fr
W_m

Fig. 6