Analysis of the Vading Concept – a new rotary-piston compressor, expander, and engine principle

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Abstract: A novel concept for rotary machines is described. A rotor is positioned acentrically in a cylindrical cavity. One or more (typically, three or four) vanes slide radially in slots in the rotor. The vanes are connected to an axle such that the tip of a vane follows the internal surface of the housing without touching it. It is shown how the concept can be utilized in the design of compressors, expanders, and internal-combustion engines. A thermodynamic model is formulated for the engine process, and calculations for a chosen set of geometrical data are presented. It is concluded that the machine can be described mathematically, and that it can work as claimed by the inventor, K. Vading. Some potential advantages over other concepts are discussed.

Keywords: rotary-piston engine, compressor, expander, gas-liquid mixtures

1 Introduction

Over the past two centuries, a large number of engine concepts have been presented. The dominating system is the reciprocating-piston engine, such as the Otto and Diesel engines for internal combustion. The reciprocating movement requires a large counterweight. Rotary engines require only a small counterweight. For internal combustion engines, several processes can take place for each rotation. Rotary engines are therefore potentially more compact. In spite of this, engines utilizing the Wankel principle are the only rotary-piston engines that have achieved moderate success. For external combustion engines, gas turbines are in widespread use. Turbines also dominate other expander applications. For compression devices, a variety of principles are in use.

In this paper, an innovative principle for rotary machines, the Vading Concept, is described. It was invented and developed by Kjell Vading of Bodø, Norway, together with his son Ketil Vading. The concept was patented internationally in 1999[1], and tested in prototypes of a gasoline motor, and of compressors and expanders for gas and for gas-liquid mixtures. The author had the opportunity to work with the Vadings and to offer some necessary scientific assistance in the development[2].

In the following, first the geometry of the concept is analysed. Then, its application as a compressor, as an expander, and an internal-combustion engine is described. The subsequent sections present the thermodynamic analysis and some calculations for a chosen set of geometrical data. Finally, the calculations, the concept, and its potential applications are discussed. The purpose of this analysis was to validate the operation and to investigate the possibilities of the concept. Optimization of the engine will be a later stage of the development.

With the exception of the patent documents, this paper is the first public presentation of the concept.

2 Geometry

The machine comprises a stationary housing with a cylindrical cavity. The rotor is positioned acentric in this cavity. One or more (typically, three or four) vanes slide radially in slots in the rotor. The working chamber is defined by the internal surface of the housing, the peripheral surface of the rotor, and one or two vanes. During a rotation, the tip of a vane describes a cylinder surface that is similar to the internal surface of the housing. The difference between these two cylindrical surfaces is a tolerance that can be chosen to be as small as it is practical to make it.

Each vane is articulately connected about an axis to a control arm. This arm is pivotally journalled in a fixed axle shaft having a central axis coincident with the axis of the cavity of the housing. The rotor axis is parallel with and non-coincident with the axis of the cavity. Power transfer to or from the machine is directly through the rotor. Further geometrical and mechanical details are given in the patent[1].

The circles in Fig. 1 indicate the inside of the housing, with radius R_2, and the periphery of the rotor with radius R_1. The centers of the circles are offset by a distance d. The Cartesian coordinates (x, y) and the polar coordinates (r, θ) are shown in the figure. The center of the rotor was chosen as the origin of the coordinates. The distance from the origin to the surface of the housing is denoted R_h and is a function of the angular position θ. The gap between the rotor and the housing at a certain angle θ is denoted s, that is Figure 1

$$s(\theta) = R_h(\theta) - R_1. \tag{1}$$

In Figure 1, the housing and the rotor are tangenting at $\theta = \pi/2$, however, this is not a requirement. If $R_2 - R_1 < d$, the circles will intersect, and the function s will be less than zero at $\theta = \pi/2$. In this case, a lune-shaped groove corresponding to the rotor has to be cut in the inside surface of the housing. For a chosen set of the radii R_1 and

R_2, the angular positions where the cylinder peripheries intersect can be found.

With the described measures and coordinates, the position of the outer circle can be found from

$$R_h(\theta) = -d\sin\theta + \left(d^2\sin^2\theta + (R_2^2 - d^2)\right)^{1/2}. \tag{2}$$

The area confined by the two circles and two angular positions, θ_1 and θ_2, can be found from integrating

$$A = \frac{1}{2}\int_{\theta_1}^{\theta_2} (R_h^2 - R_1^2)d\theta \tag{3}$$

This area multiplied by the extension in the axial direction is the volume of the working chamber.

The compression and expansion volumes are defined by vanes that are sliding in the rotor. As described above and in the patent, these vanes are guided such that the volume is enclosed. Figure 2 shows the geometrical principles of the vanes of a Vading machine. The tip of the vane is the surface of a cylinder segment with radius R_4 about the joint L. The midpoint of the vane tip is denoted B, and the point tangenting the internal surface of the housing is denoted A. The control arm linking the vane to the axle shaft has length R_3 from the center of the shaft (denoted S) to the joint, L. Figure 2

The distance R_a from origo to point A can be expressed from the right-hand side of Eq. 2 by replacing θ by $\theta - \gamma$. If the vane thickness is neglected, R_a equals R_h.

The rotor is centered on the origin, O. The vane is sliding in a slot in the rotor, and its centerline is always directed towards the origin. Therefore, the sum of the vane radius R_4 and the arm length R_3 is equal to the housing cavity radius R_2, except for a small, chosen tolerance. This requires a minimum thickness of the vane equal to two times the maximum value of the length c between the points A and B in Fig. 2:

$$c_{\max} = d \cdot R_4/R_3. \tag{4}$$

The rotor and the housing can be sectioned in the axial direction, with different dimensions for the different sections. Each section is then a separate compressor or expander of the type described below. This is indicated in Fig. 3, where one section is a compressor, and one section is an expander. The vanes will be continuous in the axial direction, with radial lengths corresponding to the dimensions of each section. The sections can be used independently, or they can be used in series. Fig. 3

The following description is for a device with three vanes, that is, with an angle of 120° between the vanes. The position of vane 1 will be denoted θ_1, and for vanes 2 and 3 the position will be $\theta_2 = \theta_1 + 120°$ and $\theta_3 = \theta_1 + 240°$. The volume or chamber in front of vane 1, that is, between vanes 1 and 2, will be called chamber 1 and the volume denoted V_1. A superscript will denote the position of vane 1 in degrees. Thus, V_1^{230} is the volume between vanes 1 and 2 when vane 1 is at $\theta = 230°$.

3 Operation

Compressor

With reference to Fig. 1, the rotor is running counter-clockwise. The maximum volume between vanes 1 and 2, is found when the vanes are in positions $\theta_1 = 210°$ and $\theta_2 = 330°$. The inflow channel is carved in the housing and ends at $\theta = 210°$. This situation is sketched in Fig. 4 Here, the actual thickness of the vanes is not shown. Fig. 4

As vane 1 moves from $\theta_1 = 90°$ towards $\theta_1 = 210°$, chamber 1 will expand and be filled with inflowing gas. When $\theta_1 = 210°$ is reached, the inflow channel in the housing ends, and the chamber between vanes 1 and 2 will be closed. Further rotation will reduce the volume, and the fluid will be compressed. Figure 5 is a sketch for $\theta_1 = 255°$. The outflow channel in the housing can begin at any position between $\theta = 330°$ and $\theta = 450°$. Fig. 5

The position of the vanes opens or closes the working chamber towards the inflow and outflow channels. Therefore, no valve or external mechanism is needed for this purpose.

Expander

The expander process is similar to the compressor process. In this case, the inflow channel in the housing has to end at some position before $\theta = 210°$. When vane 1 reaches the end of the inflow channel, the chamber will be closed. Further rotation will increase the volume until $\theta_1 = 210°$ is reached. The chamber between vanes 1 and 2 then has its maximum volume. Vane 2 will then have position $\theta_2 = 330°$. The outflow channel in the housing will begin at this position, and the fluid will be released from the expander.

Engine, motor

Using the described compressor and expander, an internal combustion engine can be designed. Basically, an internal combustion engine comprises compression, combustion, and expansion. A combustion chamber can be placed between the compressor and the expander described above. This would be similar to a gas-turbine process. Moreover, the Vading motor was designed such that the compressor and the expander can be built into one unit, where combustion takes place in a short channel or combustion chamber between the compressor and the expander. Alternatively, the combustion can partly take place in the expander.

The engine is similar to the compressor and expander. Air, or premixed air and fuel, is compressed in the first section. The compressed gas is then released through a channel or combustion chamber to the next section in the axial direction, which is the expander. The gas is compressed between two of the vanes and expands between the same two vanes in the expander. Since the radial dimensions of the compressor and the expander are different, the compression and expansion ratios can be varied independently. This is contrary to the Otto and Diesel processes, where compression and expansion take place in the same volume.

In this study, a 3-vane version of the Vading engine was analyzed. However, the concept can also be designed with two, four, or more vanes.

4 Thermodynamic analysis of the Vading engine

This section presents a simple thermodynamic analysis of the processes occuring in the Vading engine. The analysis was based on idealizations similar to those made in textbook presentations of the conventional engines (e.g. Otto and Diesel engines).

Assumptions and simplifications for the thermodynamic analysis:

- Operational conditions were steady.
- At any instance, pressure, temperature, and concentration of chemical species were uniform throughout the investigated volume. This implies, e.g., that effects of the flow field were neglected.
- The combustion was complete and instantaneous, i.e., infinitely fast. This also implies that the combustion process was adiabatic.
- Heat losses during expansion and compression were neglected, and these processes were isentropic.
- The specific heating capacities were constant and equal for air, fuel, and products.
- Leakages and friction were neglected.
- The volume of the vanes was neglected when gas volumes were calculated.

The engine process can be described schematically by the flowsheet in Fig. 6. The process takes place between vanes 1 and 2, i.e. in chamber 1. The inlet channel in the housing ends at the angular position θ_{in}, and chamber 1 is closed from the inlet when vane 1 is at $\theta_1 = \theta_{\text{in}}$. For a 3-vane engine, $\theta_{\text{in}} = 210°$. Then, vane 2 is at $\theta_2 = 330°$, and the enclosed compressor volume has its maximum value, $V_{c1}^{210} = V_{c,\max}$. The gas is compressed until $\theta_1 = \theta_c$, where the inlet to the combustor opens. With further rotation, the gas is compressed into the combustor, and the compressor volume is reduced to zero. The value of θ_c has to be decided in the design of the specific engine. Figure 6

At a certain position, $\theta_1 = \theta_{\text{cb}}$, the air-fuel mixture is ignited. The combusted gas is led to the expander. At the position $\theta_1 = \theta_e$, the channel to the expander ends, and the gas is enclosed in the expander. Some of the gas is trapped in the combustor volume. This gas is mixed with the next portion of compressed gas that is about to enter the combustor. This results in a recirculation as shown in the flowsheet, Fig. 6. The expansion continues between vanes 1 and 2 until vane 2 reaches the exhaust outlet channel where $\theta_1 = \theta_{\text{out}}$ (i.e., $\theta_2 = \theta_{\text{out}} + 120°$).

The analysis below was based on the mass balances following from the flow sheet in Figure 6, the ideal-gas equation of state, and the isentropic pressure-volume relationship. The energy balances are also in accordance with the flow sheet. The heating value of the fuel was released at a certain instance (i.e., at a certain angular position), and the temperature increased correspondingly.

Forces and moment

The gas exerts a force on the vanes in both angular directions. In a compressor, the visible area of vane 1 is larger than that of vane 2, therefore, the moment acts against the motion. Similarly, in an expander the net force acts in positive direction.

The moment arm is the radius of the rotor plus half the height of the visible vane, and thus, nearly constant during a process.

Compression ratio

For conventional reciprocating-piston engines, the compression ratio is an important parameter defined by the ratio of the maximum volume to the minimum volume. For a regular cylinder, this ratio is readily found when diameter, stroke length, and top clearance are known. For the Vading engine, the geometry is more complex, and the volumes for compression and expansion are different. Moreover, some mass is contained at a certain pressure in the combustor between the compression and expansion chambers. If this recirculated mass is significant compared to the inflow mass, the ratio of absolute volumes will be rather misleading. The compression and expansion ratios must be expressed in terms of specific volumes,

$$\frac{v_{\text{max}}}{v_{\text{min}}} = \frac{V_{\text{max}}}{V_{\text{min}}} \cdot \frac{(m_{\text{in}} + m_{\text{rec}})}{m_{\text{in}}}. \tag{5}$$

Here, the maximum volume, V_{max}, is different for compression and expansion. Under steady operating conditions, the inlet mass, m_{in}, equals the outlet mass, cf. Fig. 6. The recirculated mass, m_{rec}, is the mass within the combustor just before the expander volume is closed. Thus, the ratio can be expressed

$$\frac{m_{\text{rec}}}{m_{\text{in}}} = \frac{V_{\text{cb}}}{V_{\text{1e}}^{\theta e}}. \tag{6}$$

Here, V_{cb} is the volume of the combustor, and $V_{\text{1e}}^{\theta e}$ is the volume of the expansion chamber at the position $\theta_1 = \theta_e$, where the expander is closed.

5 Calculations for an engine utilizing the Vading Concept

This section describes the test simulation done using the geometrical and thermodynamic models developed above.

The engine dimensions used in the calculations are listed in Table 1. The inlet volume becomes $V_{1c}^{210} = 147\,\text{cm}^3$. This is the maximum volume of the compressor. The ratio Table 1 of this volume to the minimum volume is $V_{1c}^{210}/V^{384} = 8.4$. The minimum volume, with the given dimensions, is found at $\theta_1 = 384°$. For the expansion, the ratio of the maximum volume to the minimum volume is $V_{1e}^{570}/V^{384} = 18.1$. As noted above, these ratios are not equal to the compression and expansion ratios.

The fuel in the calculations was methane, which burned with 210% theoretical air. The full process takes two rotations, and here it was calculated from vane 1 position $\theta_1 = 0°$ to $\theta_1 = 720°$ in steps of 1°.

Figure 7 shows the volume as a function of the rotation angle of vane 1, θ_1. The inlet channel closes when $\theta_1 = 210°$, and the outlet channel opens when $\theta_1 = 570°$. Outside this interval, the volume cannot be calculated, and the pressure is equal to the environmental pressure. The pressure and temperature of the process are shown in Fig. 8. The combustion takes place at $\theta_1 = 390°$.

Figure 7

Figure 8

In a Vading engine with three vanes, six processes take place at one instance in the same chamber with a 120° displacement. One process is completed at every one-third of a rotation. The moment from a single process is shown in Fig. 9. The figure also shows the total moment from all six processes.

Figure 9

6 Discussion

Discussion of calculations

The calculations presented were done for demonstration purposes, and some idealizations and simplifications were made. Therefore, the presented calculations are similar to those presented in e.g. textbooks for conventional machines.

For simplicity, the thickness of the vanes was neglected. For a detailed optimization of a particular device, accurate volumes can be calculated from the geometry of the vanes.

Discussion of the concept

A machine utilizing the Vading Concept is characterized by few parts that are simple to manufacture. The machine appears to be robust and compact.

To some extent, this rotor-stator-vane arrangement is similar to the rotary-vane compressor concept. However, Vading's principle ensures that the vanes follow the housing without touching it. This eliminates the wear problem typical of some rotating machines.

An engine of this type has separate chambers for compression and expansion. This means that the local temperature variation is less than that of a reciprocating-piston engine. Furthermore, the compression and expansion ratios can be optimized independently. In this instance, the Vading engine is similar to the gas-turbine process. On the other hand, the material of the vanes is significantly thicker than that of the gas-turbine blades. Consequently, it seems reasonable that the Vading engine, as the reciprocating-piston engines, can withstand a higher maximum temperature than that of a gas turbine. Thus, the potential efficiency should be higher.

The Vading engine is a rotary engine and, therefore, needs no counterweight. The working force has a nearly constant and substantial moment arm about the shaft. Moreover, the radial forces on the rotor generated in the compression and expansion chambers counteract each other.

Prototypes and testing

Several prototypes of the machine have been built. The housing was made of 36 mm steel plates. This allowed new aspects of the machine to be tested simply by modifying or replacing one or two of these plates.

The first prototype was a gasoline engine with three vanes, two compressor sections, and a combustor and an expander between these two sections. There was no auxiliary cooling, so the engine was only allowed to run a few minutes each time. Another prototype was built as a single-section expander. This could be converted to a compressor by changing one of the steel plates in the housing. This prototype was tested in the high-pressure laboratory at Statoil Research Center in Trondheim.

The results of the testing were very promising. In particular, the performance of the compressor and expander working with gas-liquid mixtures was very good[3].

Applications

For these types of products, industrial users and private consumers favor conventional, well-proven technology. Therefore, a new concept has to have substantial benefits to be able to compete on the market. However, there may be niches where conventional technology is not well proven or has in fact proven insufficient.

It appears that the Vading machine performs well with gas-liquid mixtures. In particular, there seem to be few expanders on the market for this type of flow. Three possible applications can be mentioned:

– Expansion of saturated or low-superheated steam into the wet area, i.e. with condensation in the expander. Some work can then be produced in a cogeneration plant without an expensive superheater.

– Utilizing high pressure in oil and gas wells. This pressure is usually reduced by throttling. The Vading Concept would allow utilization of this excess pressure.

– Replacment of the expansion valve in vapor-compression refrigeration or heat-pump cycles. The Vading Concept would allow utilization of the expansion in the two-phase area.

As an external-combustion engine, the Vading engine may be operated with continuous, pulsating, or intermittent combustion.

7 Concluding remarks

The geometry, functionality, and thermodynamic processes of Vading machines have been investigated. The geometry is described mathematically, and it is shown that the working volume is enclosed by the housing, the rotor, and one or two vanes, as claimed by the inventor. It is also shown that the tip of a vane will always follow the internal surface of the housing. The processes are described and modeled mathematically, and for demonstration purposes, calculations for a chosen set of geometrical data were performed.

An issue still to be solved is the specific arrangement and design of the combustor in a Vading engine. Furthermore, the optimization of particular devices requires further investigation.

Acknowledgements

During the project, I have had many long and interesting discussions with the inventor, Kjell Vading, Bodø, Norway. Furthermore, discussions with my colleague Professor Bjørn F. Magnussen are greatly appreciated.

References

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Tables

Table 1: Dimensions used in the simulation of a Vading engine

R_{1c}	R_{2c}	R_{1e}	R_{2e}	d	L_c	L_e	V_{ch}
0.127 m	0.140 m	0.147 m	0.160 m	0.015 m	0.02 m	0.03 m	$10.21 \cdot 10^{-6}$ m^3

Figures

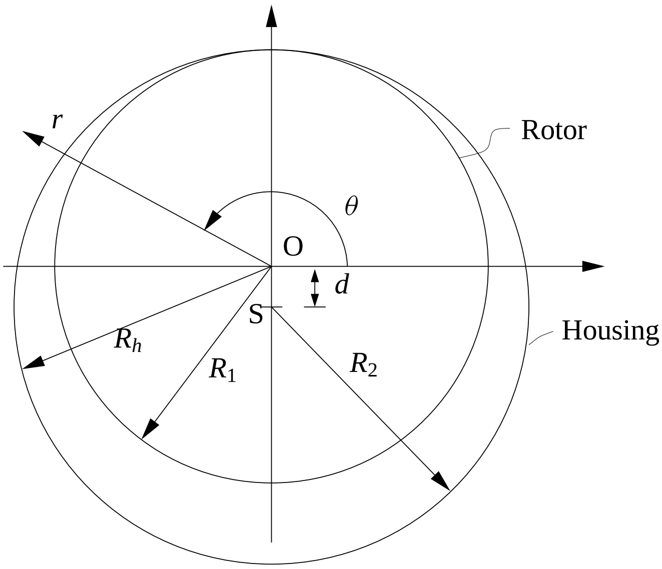

Figure 1: Coordinates and basic geometry of the Vading Concept

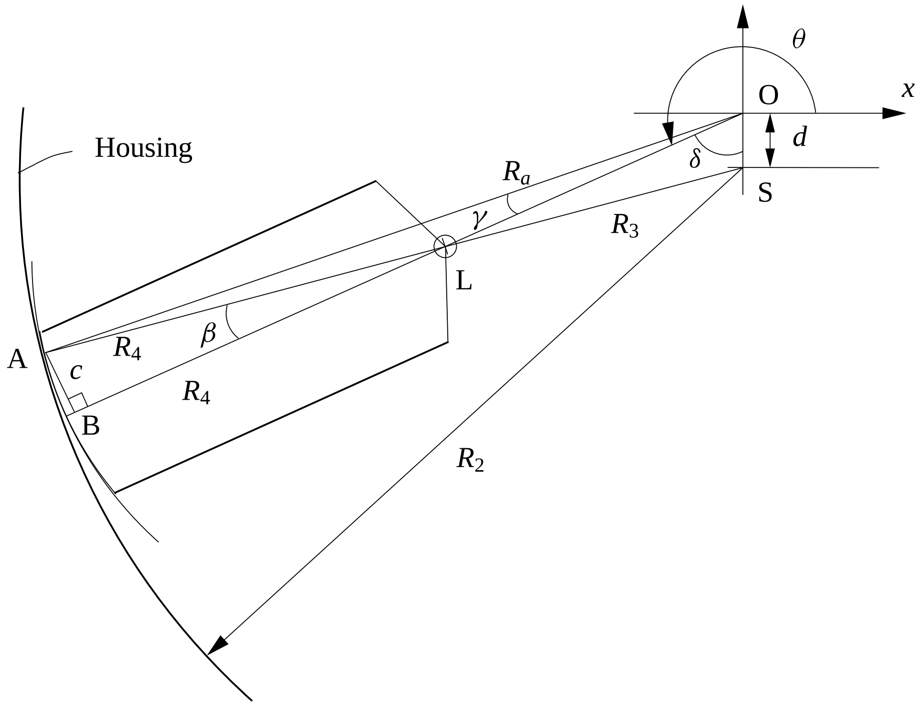

Figure 2: Geometry of the vane-arm-shaft arrangement of the Vading Concept

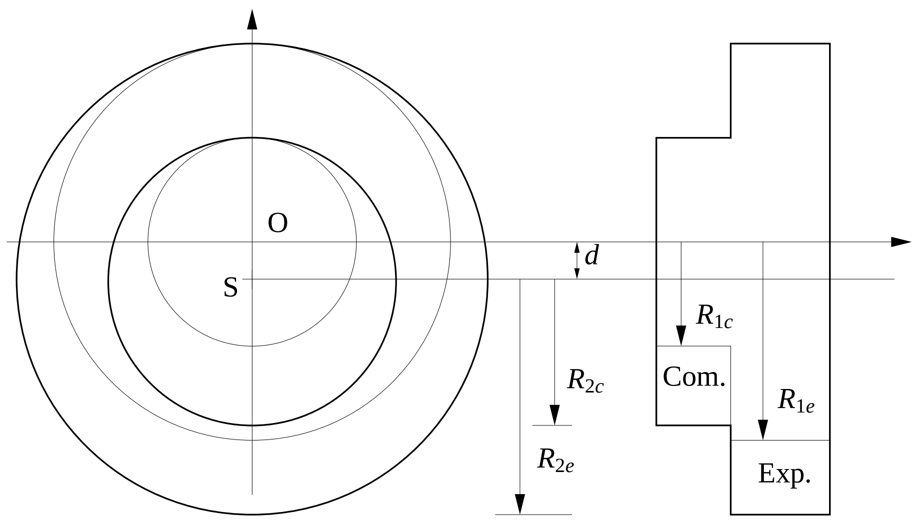

Figure 3: Projection of engine, i.e. combined compressor and expander in one engine

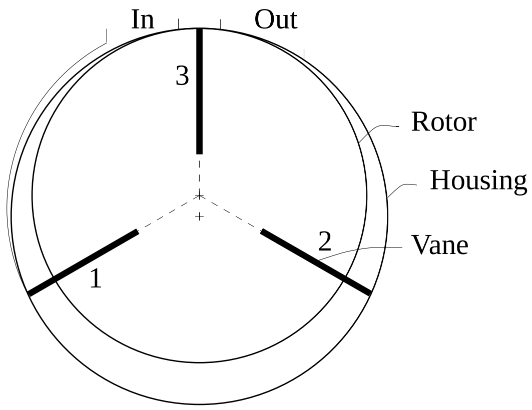

Figure 4: Compressor when vane 1 is at 210°: Inflow channel (indicated) is closed. The volume between vanes 1 and 2 is at maximum. The compressed gas between vanes 2 and 3 is released through the outflow (indicated). Note: Figure does not show the actual vane thickness.

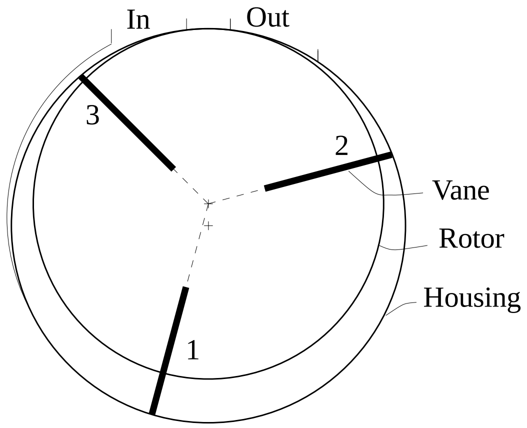

Figure 5: Compressor when vane 1 is at 255°: The volume between vanes 1 and 2 is decreasing; the volume between vanes 3 and 1 is increasing and filled through the inflow channel (indicated).

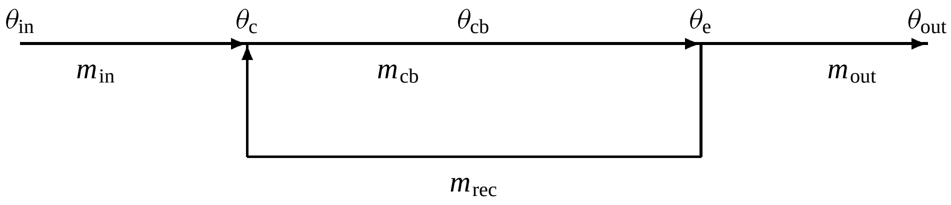

Figure 6: Flow sheet of the mass flow of the engine process

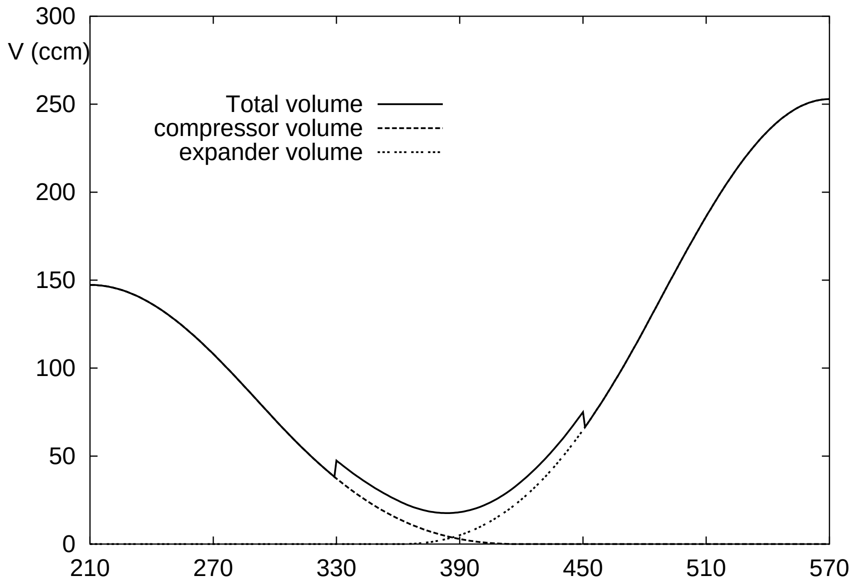

Figure 7: Volume [cm^3] in compression chamber, expansion chamber, and total process volume as functions of the position of vane 1, θ_1 [°].

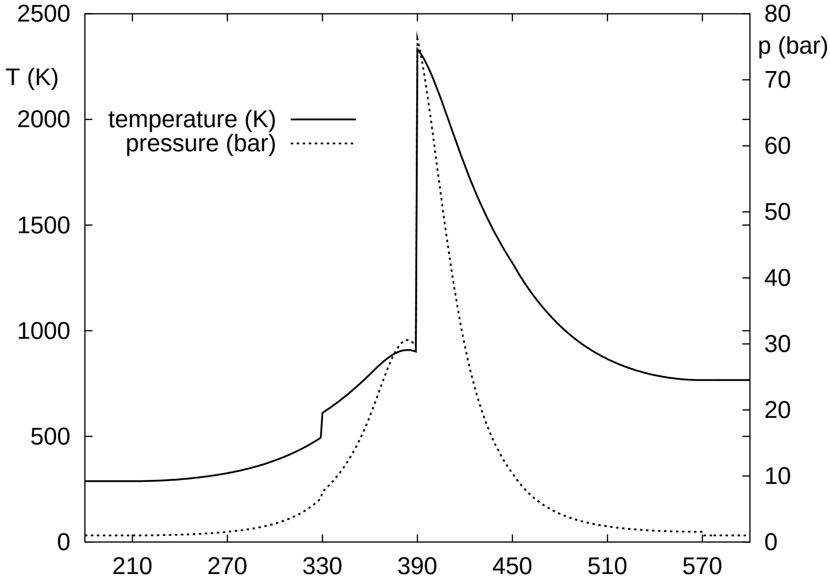

Figure 8: Temperature (left) and pressure (right) as functions of the position of vane 1, θ_1 [°]. The combustion takes place at $\theta_1 = 390°$.

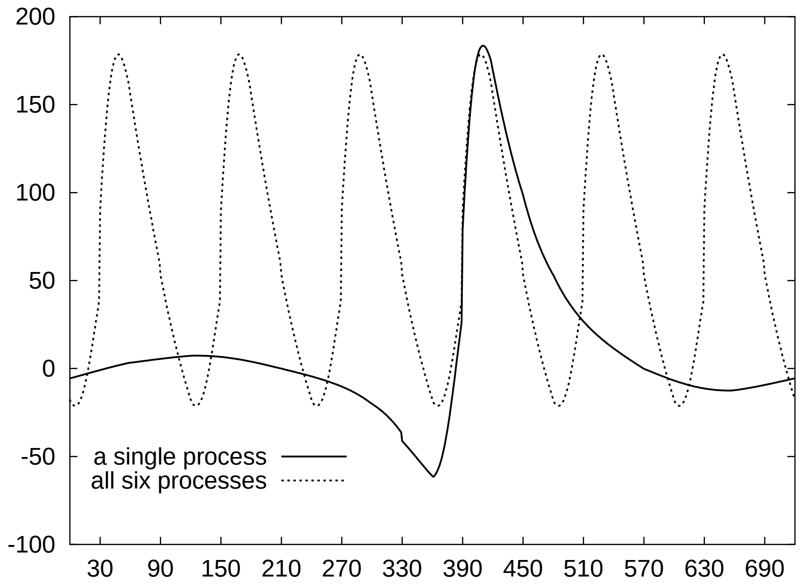

Figure 9: Moment [Nm] from a single process, and total moment from all six processes working at the same time. The combustion takes place at $\theta_1 = 390°$.