A New Class of Heat Engine for Space Application

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A new class of heat engine succeeds in the direct conversion of thermal/kinetic energy to a sustained accelerative vector force without the expulsion of reaction mass. No Newtonian principle is violated, and mass, energy, and momentum are conserved. These engines rely upon the properties of a gas in steady-state flow in a recirculating duct, and the manipulation of the density and velocity of this gas by means of thermal management. The resulting propulsion system is a conventional heat engine in all respects except that it offers a self-referential method of accelerating itself and an attached mass given a source of energy and a means of cooling. The engine is simple in concept and design, scalable, and may contain only one moving part. This article describes the theory of operation and the working prototypes (TRL-4), and proposes the application of the method.

Nomenclature

\[ A = \text{Cross sectional area of duct (constant)} \]
\[ F_1 = \text{Force acting along Y axis in Turn 1} \]
\[ F_2 = \text{Force acting along Y axis in Heat Exchanger} \]
\[ F_3 = \text{Force acting along Y axis in Turn 2} \]
\[ F_4 = \text{Force acting along Y axis in Impeller Section} \]
\[ F_R = \text{Resultant accelerative force acting along Y axis} \]
\[ \Delta V = \text{Change in velocity} \]
\[ g_c = \text{Gravitational constant} \]
\[ I_sp = \text{Specific Impulse} \]
\[ p_1 = \text{Pressure of gas in Turn 1} \]
\[ p_2 = \text{Pressure of gas in Turn 2} \]
\[ M_0 = \text{Mass (wet) of a space vehicle} \]
\[ M_b = \text{Mass of a space vehicle at burnout (dry) including payload} \]
\[ m_1 = \text{Mass of gas contained in volume } V_1 \text{ of Turn 1} \]
\[ m_2 = \text{Mass of gas contained in volume } V_1 \text{ of Turn 2} \]
\[ m_e = \text{Mass of gas contained in the heat exchanger} \]
\[ m_i = \text{Mass of gas contained in the impeller section} \]
\[ r_1 = \text{Radius of Turn 1} \]
\[ r_2 = \text{Radius of Turn 2} \]
\[ T_1 = \text{Temperature of gas in Turn 1 (entering heat exchanger)} \]
\[ T_2 = \text{Temperature of gas in Turn 2 (exiting heat exchanger)} \]
\[ t_1 = \text{Duration of transit of gas mass } m_1 \text{ through Turn 1} \]
\[ V_1 = \text{Volume of gas in Turn 1 and Turn 2} \]
\[ V_2 = \text{Volume of gas containing mass } m_1 \text{ in Turn 2} \]
\[ v_1 = \text{Velocity of gas in Turn 1} \]
\[ v_2 = \text{Velocity of gas in Turn 2} \]

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I. Introduction

All space vehicles now rely for their propulsion upon reaction engines that expel a reaction mass from the vehicle, and most such vehicles use this technology for positioning and orientation. Konstantine E. Tsiolkovsky first described the performance of reaction engines in the year 1903 as:

\[ \frac{M_0}{M_b} = \exp(\Delta V / g_c I_{sp}) \]

\[ M_b = M_{dry} + M_{payload} \]

The wet mass of the vehicle \( M_0 \) is therefore a function of the dry mass \( M_b \) of the vehicle and its payload, and a function of the specific impulse \( I_{sp} \) and the desired velocity increase \( \Delta V \). The specific impulse \( I_{sp} \) typically ranges from 200-450 seconds for chemical rocket engines and from 1,000-3,300 seconds for the electrical reaction engines now available. Work to improve the performance of vehicles employing reaction engines usually addresses an increase in specific impulse \( I_{sp} \), and/or a decrease in the dry mass of the vehicle \( M_{dry} \) and its payload \( M_{payload} \). Chemical rocket engines are limited by the materials and fuel employed to their present specific impulse and little improvement is anticipated. Electrical reaction engine methods offer high specific impulse, but low thrust to mass ratios. Reaction engines are considered to be the only practical propulsive method for space vehicles because such a vehicle operates as an independent or closed frame of reference.

It is accepted as fact that nothing that occurs in a closed frame of reference (“Newton’s Box”) may result in the sustained acceleration of that frame if mass, energy and momentum are conserved within that frame. No manipulation of any kind has succeeded in violating this precept, and the engine described in this article offers no such violation. The mass within the frame comprised by this engine and any attached mass is conserved, and the momentum of this mass is also conserved. Energy, however, is permitted to transit the frame and to do work within it, and is conserved as observed from outside of the frame. No unusual circumstance or special exception to Newtonian physics is necessary to completely describe the operation of these engines. The operating principle and its physical embodiment are straightforward, and should prove to be responsive to the methods of analysis and engineering improvement that apply to any heat engine. A previous report described the derivation of the theory of operation of the method, and the design and test of the proof of concept prototypes. This article addresses the limitations of the method, and suggests certain applications.

Figure 1. Annotated schematic of engine
II. Theory of Operation

Three well understood principles are called upon in the following theory of operation: Newton’s laws of motion, Bernoulli’s theorem, and the ideal gas law. The analysis is in m•v form, and since the prototypes operate at near ambient temperatures and pressures, the approximations imposed by the simplification of the gas equations do not obscure the results. Of course, any attempt to optimize the method will take advantage of more rigorous methodology.

Please refer to Fig. 1. The following is a description of the interaction between the mass, velocity, temperature and pressure of the recirculating gas contained in this duct, and the resultant sustained accelerative force $F_R$. The assumption is made that the $2\pi$ symmetry of the duct would result in any vector force not acting along the y-axis being canceled by an equal and opposite vector force, and that only y-axis forces need to be considered. The gas flow is assumed to have achieved a steady state, and the centripetal force resulting from the flow of the gas in Turn 1 multiplied by the integral of sin $a$ ($0, \pi$) is defined as a y-axis force $F_1$ (N) acting in the positive y direction:

$$F_1 = \left(\frac{m_1 v_1^2}{r_1}\right) \int_{a=0}^{\pi} \sin a \quad \text{where: } v_1 = \frac{\pi r_1}{l_1} \quad (1)$$

$$F_1 = \frac{2m_1 \pi r_1}{l_1} \quad (2)$$

Gas exiting Turn 1 at velocity $v_1$ (m/s), temperature $T_1$ (K), and pressure $p_1$ (kPa) enters the heat exchanger section and is cooled to temperature $T_2$ (K) at pressure $p_2$ (kPa), and slowed to velocity $v_2$ (m/s), resulting in force $F_2$ (N) that acts in the negative y direction:

$$F_2 = -\frac{m_e(v_1-v_2)}{r_e} \quad \text{for: } \frac{m_e}{r_e} = \frac{m_1}{l_1} \quad (Bernoulli’s \ theorem), v_1 = \frac{v_1}{A_{l_1}}, v_2 = \frac{v_2}{A_{l_1}} \text{ and } V_2 = V_1 \left(\frac{T_2 p_1}{T_1 p_2}\right) \quad (3)$$

$$F_2 = -\left(\frac{m_1}{l_1}\right) \left(\frac{v_1}{A_{l_1}} - \frac{v_2 T_2 p_1}{A_{l_1} T_1 p_2}\right) \quad (4)$$

$$F_2 = -\left(\frac{m_1}{l_1}\right) \left(\frac{v_1}{A_{l_1}} \left(1 - \left(\frac{T_2 p_1}{T_1 p_2}\right)\right) \quad \text{and: } V_1 = \pi r_1 A \quad (5)$$

$$F_2 = -\left(\frac{m_1 r_1}{l_1} \right) \left(1 - \left(\frac{T_2 p_1}{T_1 p_2}\right)\right) \quad (6)$$

In Turn 2, the centripetal force resulting from the flow of the gas contained in the volume of Turn 2 multiplied by the integral of sin $b$ ($\pi, 2\pi$) equals the y-axis force $F_3$ (N) acting in the negative y direction:

$$F_3 = \left(\frac{m_2 v_2^2}{r_2}\right) \int_{b=\pi}^{2\pi} \sin b \quad (7)$$

$$F_3 = -\frac{2m_2 v_2^2}{r_2} \quad (8)$$

The volume of Turn 2 (not quantity $V_2$) is defined as being the same as that of Turn 1 ($r_2 = r_2$, $A = constant$), or $V_1$, and is defined as containing mass $m_2$ (kg). The volume of gas $V_2$ (pressure and temperature dependent) is defined as containing mass $m_1$ (kg), therefore:

$$m_2 = m_1 + \frac{m_1 (v_1-v_2)}{v_2} = m_1 \left(1 + \frac{v_1-v_2}{v_2}\right) \text{ where: } V_2 = V_1 \left(\frac{T_2 p_1}{T_1 p_2}\right) \text{ and: } \frac{v_1-v_2}{v_2} = \left(\frac{T_2 p_1}{T_1 p_2}\right) - 1 \quad (9)$$

$$m_2 = m_1 \left(\frac{T_2 p_1}{T_1 p_2}\right) \text{ and: } v_2 = \frac{v_2}{A_{l_1}} = \left(\frac{V_2}{A_{l_1}}\right) \left(\frac{T_2 p_1}{T_1 p_2}\right) \quad (10)$$

$$F_3 = -\frac{2m_1}{\pi} \left(\frac{T_2 p_1}{T_1 p_2}\right) \left(\frac{v_2 T_2 p_1}{A_{l_1} T_1 p_2}\right)^2 \text{ where: } V_1 = \pi r_1 A \text{ and: } r_1 = r_2 \quad (11)$$
\[ F_3 = -\frac{2m_1 \pi^2 r_2 T_2 p_1}{t_1^2 t_1 p_2} \]  \hfill (12)

The impeller section serves to increase pressure \( p_2 \) to pressure \( p_1 \), and temperature \( T_2 \) to temperature \( T_1 \). This results in an increase in gas velocity from \( v_2 \) to \( v_1 \), and a y-axis force \( F_4 \) (N) acting in the negative y direction:

\[ F_4 = -\frac{m(t_1 - v_2)}{t_1} \quad \text{where:} \quad \frac{m}{t_1} = \frac{m_1}{t_1} = \frac{m_2}{t_2} \]  \hfill (13)

\[ F_4 = -\frac{m_2(v_1 - v_2)}{t_2} \]  \hfill (14)

Therefore, from the heat exchanger discussion above, \( F_2 = F_4 \):

\[ F_4 = -\left( \frac{m_1 \pi r_1}{t_1^2} \right) \left( 1 - \left( \frac{T_2 p_1}{T_1 p_2} \right) \right) \]  \hfill (15)

Summing the \( F_R \) forces:

\[ F_R = F_1 + F_3 + F_2 + F_4 \]  \hfill (16)

\[ F_R = \left( \frac{2m_1 \pi^2 r_1}{t_1^2} \right) + \left( -\frac{2m_1 \pi^2 r_2 T_2 p_1}{t_1^2 t_1 p_2} \right) + 2 \left( -\frac{m_1 \pi r_1}{t_1^2} \right) \left( 1 - \left( \frac{T_2 p_1}{T_1 p_2} \right) \right) \text{ then for: } r_1 = r_2 \]  \hfill (17)

\[ F_R = \left( \frac{2m_1 \pi^2 r_1}{t_1^2} \right) \left( 1 - \left( \frac{T_2 p_1}{T_1 p_2} \right) \right) - \left( \frac{2m_1 \pi r_1}{t_1^2} \right) \left( 1 - \left( \frac{T_2 p_1}{T_1 p_2} \right) \right) \]  \hfill (18)

\[ F_R = (2\pi - 2) \left( \frac{m_1 \pi r_1}{t_1^2} \right) \left( 1 - \frac{T_2 p_1}{T_1 p_2} \right) \quad \text{and: } \quad t_1 = \frac{\pi r_1}{v_1} \]  \hfill (19)

\[ F_R = \left( 2 - \frac{2}{\pi} \right) \left( \frac{m_1 \pi^2 r_1}{t_1^2} \right) \left( 1 - \frac{T_2 p_1}{T_1 p_2} \right) \]  \hfill (20)

The first term of Eq. (20), \((2 - 2/\pi)\), is dependent upon the placement of the impeller between the exit from Turn 2 and the entry to Turn 1. For example, this term will become \((1/2 - 1/\pi)\) with the impeller at the midpoint of Turn 1, and \((0)\) with the impeller placed at the exit of Turn 1 with corresponding reductions in the accelerative force \( F_R \).

The second term of Eq. (20), \((m_1 v_1^2/r_1)\), is Newton’s formula for centripetal force, and defines the effect of changes in the mass, velocity, and path of the recirculating gas.

The third term of Eq. (20), \((1 - T_2 p_1/T_1 p_2)\), addresses the state of the recirculating gas. If the internal processes of the device are adiabatic \((T_2 p_1/T_1 p_2 = 1)\), then the accelerative force \( F_R \) output will equal zero. This supports one of the fundamental assumptions of the “Newton’s Box” concept, that if energy is conserved within the box no sustained acceleration is possible. However, if energy is permitted to transit the box as outlined above and if the physical arrangement of the duct is as described, then if the product of the temperature ratio \( T_2 / T_1 \) and the pressure ratio \( p_1 / p_2 \) is less than unity a sustained accelerative vector force \( F_R \) must result.

Therefore, as pressure ratio \( p_1 / p_2 \) is greater than unity because of the action of the impeller, it is necessary to ensure that the temperature ratio \( T_2 / T_1 \) is correspondingly reduced. In the prototypes, this was a consequence of the losses of an inefficient impeller design, and in the case of the Bootstrap VI and VII prototypes, the location of the impeller motor in the recirculating gas. Additional heat input after the impeller and before the entrance of Turn 1 would further increase temperature \( T_1 \) and the accelerative force \( F_R \) output provided that temperature \( T_2 \) is not proportionally increased.

Equation (20) takes no note of the fluid dynamics of the gas, the thermal or mechanical properties of the device structure, or the characteristics of the impeller-driver. Any practical application of this method will require design-specific analysis beyond the scope of this article, but the above cautions will apply.

The form factor of these propulsion systems may be tailored to suit a particular application, with ducts of varying area and turns of varying radius. The \( 2\pi \) symmetry and the identical turns at both ends of the prototype designs were
chosen to minimize unbalanced off-axis internally generated forces, and for the minimum complexity of the analysis and construction of the prototypes. Other arrangements, such as reflective symmetry, paired individual systems, and endless other forms have their own advantages. It should be mentioned that the $2\pi$ configuration does offer a volume of unused space inside the outer pressure shell of the engine, and that such a space might prove useful in certain applications.

III. Prototypes

A proof of concept prototype (Bootstrap VII) as illustrated in Fig. 2 operated at very low mass flow ($m_4 = 0.00078$ kg), gas velocity ($v_1 = 1.1$ m/s), temperature gradient ($T_1 = 299.5^\circ$K, $T_2 = 296^\circ$K) and pressure gradient ($p_1 = 100.2$ kPa, $p_2 = 100.0$ kPa) with both turns of equal radius ($r_{1,2} = 0.06$ m). The Bootstrap VII prototype masses 8 kg, and requires 250W at rated power. The measured sustained accelerative force output $F_R$ of this prototype ($0.00018 \pm 0.00002$N) is subject to improvement by orders of magnitude as the gas velocity, gas density, and temperature gradient of follow-on designs are increased.

However, a direct comparison of this prototype (Bootstrap VII) and the DAWN Ion Engine will illustrate the potential of the method. The Bootstrap VII prototype achieves 9% of the N/kW and 15% of the N/kg (engine plus propellant mass at launch) of the DAWN Ion Engine, but without the discharge or consumption of reaction mass.

The author chose to limit the proof of concept prototypes to identical impeller/drivers, a single duct design, and room air at 100 kPa as a working fluid. Only theory-driven changes to the location and internal flow path of the impeller section were investigated. The two prototypes Bootstrap V and Bootstrap VI, shown in Fig. 3, explored the relationship of impeller position within the duct to the accelerative force output. The location of the impeller assembly in proof of concept prototype Bootstrap V was effectively at the mid-point of Turn 1 ($a \approx 90^\circ$). This had the effect of reducing the first term of Eq. (20) to $(1/2 - 1/\pi)$. The impeller assembly in the Bootstrap VI prototype was then relocated to the entrance of Turn 1 ($a \approx 180^\circ$), which increased the first term of Eq. (20) to $(2 - 2/\pi)$, but decreased gas velocity $v_1$ by 31% to 0.9 m/s due to flow restrictions. This conflict limited the gain in $F_R$ to 14% over that of Bootstrap V.

Further investigation with the Bootstrap VII prototype addressed the flow path within the impeller section. A set of eight flow-straightening vanes was added in the outflow scroll of the impeller as shown in Fig. 3. This one change increased the gas velocity $v_1$ by 20% to 1.1 m/s, and the accelerative force $F_R$ by 14% as compared to the Bootstrap VI prototype (the accelerative force $F_R$ increased by 29% as compared to Bootstrap V).
IV. Experimental Methods

The enclosed pendulum suspension detailed in Fig. 4 supports a cradle suspended at both ends by vertical and diagonal links from four suspension points located in parallel horizontal and common vertical planes with the four cradle suspension points (at rest). Each suspension point consists of a round section polished steel hook epoxied to the suspension wires in a plane perpendicular to the Y-axis of the device under test (DUT) and a round section polished steel eye in a plane parallel to the Y-axis of the DUT at each point of contact.

Diagonal links at both ends permit the cradle to move horizontally only in the vertical plane containing the common centerline of the DUT and the cradle. Two pairs of differential support links (length proportional to the
weight supported), one pair at each end of the DUT, allow the test article to expand and contract as it changes in
temperature without shifting its center of gravity longitudinally along its centerline in the supporting cradle. The
horizontal force measurement taken from the cradle is insensitive to external convection currents which are
substantially perpendicular to the longitudinal centerline of the device and to its one degree of freedom of movement.

Power is supplied to the DUT by a twisted pair of #24AWG stranded copper power conductors suspended
vertically from the top of the enclosure (1.5 m). No magnetic field induced displacement or disturbance associated
with the 120 VAC, 2.1 ampere supply current has been observed.

All test runs begin with the DUT in an essentially isothermal state (a minimum of 20 hours since the previous
test run), typically at 286.5°K (+/- 2°K). Temperature measurements $T_1$ and $T_2$ are taken with two digital
thermometers mounted on the DUT. These devices have their sensors on the external skin of the heat exchanger, but
they have been characterized against a thermocouple temporarily located in the working mass gas flow immediately
adjacent to each external sensor.

The working mass gas velocity $v_1$ was measured by means of differential pressure measurements at two points in
Turn 1. These measurements were taken during normal operation of the DUT, but not during a logged test run as the
connections would prevent the free movement of the DUT.

Two methods have been used to measure the presence or absence of an accelerative force $F_R$ along the major
axis of the DUT. A displacement method measured the movement of the unrestrained DUT, but proved extremely
sensitive to periodic and harmonic disturbances resulting from start up and shut down transients since there was little
damping of the motion of the cradle/DUT.

A force balance method measured any accelerative force directly without interpretation. This measurement was
repeatable to ± 1mg, and was calibrated to < 2mg before and after each test run. The free pendulum period of the
cradle/DUT (Bootstrap VII) was 2.54 seconds, while the force balance damped period was 1.84 seconds. The force
balance demonstrated the harmonic motion of the attached cradle/DUT.

V. Experimental Results

Figure 5 illustrates the increase of gas temperatures $T_1$ and $T_2$ during a typical test run, and the relationship of
the heat exchanger temperature gradient “$T_1 - T_2$ (Delta T)” to input power and duration.

Figure 6 illustrates the force “$F_R$ Calc” which was calculated using Eq. (20), the gas temperatures $T_1$ and $T_2$
from Fig. 5, and the gas mass $m_1$, gas velocity $v_1$, gas pressures $p_1$ and $p_2$, and turn radius $r_{1,2}$ from the Bootstrap
VII test runs to be presented in Fig. 7. Note the delay in the onset of the increase in force $F_R$ Calc as compared to
the gas velocity “$v$ Gas” until the temperature gradient Delta T is established, and the immediate reduction in $F_R$
Calc when the gas velocity decreases.

Figure 7 illustrates the measured force “$F_R$ Average” data averaged from four test runs of the Bootstrap VII test
device on four consecutive days, presented with the calculated force $F_R$ Calc from Fig. 6. The $F_R$ Average data
proves the aliasing that results from the 6 second data sampling interval, the 1.84 second harmonic period of the
suspended test article, and the start-up/shut down disturbances of the impeller and driver.

Figure 8 illustrates the thermal expansion of the DUT along the Y-axis of the device during the test runs
illustrated in Fig. 7. This value was calculated using the thermal expansion coefficient and the length of the heat
exchanger section, and the measured surface temperatures $T_1$ and $T_2$.

Figure 9 illustrates the averaged force “$F_R$ Blocked” data from two test runs of the Bootstrap VII test device with
the return duct blocked, presented with the $F_R$ Average data from Fig. 7. No sustained gas flow $v_1$ was possible
during these operations of the DUT, and the lack of gas flow limited the duration of this exercise to four minutes at
full power. A thermally induced mechanical transient resulted in the $F_R$ excursions seen at the end of the run.
Figure 5. Measured gas temperatures
Figure 6. $F_R$ calculated using Eq. (20)

Figure 7. Measured $F_R$ Average from four consecutive test runs of Bootstrap VII compared to $F_R$ calculated

Figure 8. DUT Thermal expansion on Y-axis
Figure 9. $F_R$ Blocked measured with duct blocked
VI. Conclusions

At this point, the theoretical basis for this propulsion method is considered to be understood, but subject to much development. The theory of operation predicted and the prototypes confirmed that a method of converting thermal/kinetic energy to a sustained accelerative vector force without the discharge of reaction mass is possible and has been achieved. The proof of concept prototypes closely matched the accelerative force output expectations derived from the theory of operation and the careful measurement of their thermal, pressure, and gas flow parameters. A sustained accelerative vector force was generated without the discharge of reaction mass, which is the equivalent of an indefinitely large $I_{sp}$. Therefore, the application of this technology to future space vehicles should result in performance improvements such as increased velocity change capability, increased duration of utility, and a reduction in their mass and cost.

Recommendations

The question is, of course, how effective can this propulsion method become? Equation (20) does not incorporate the practical limitations of materials or the available power, mass, and volume of a given application, but it does facilitate an encouraging first approximation of the propulsive effect of notional engine designs.

One benefit resulting from the application of this technology should be the reduction in the launch mass of a payload vehicle due to the absence of reaction mass (fuel). In the case of a reference 1000 kg inner solar system probe using reaction engines, a change to the propulsion method here described might result in a 500 kg vehicle (solar electric) with the same instrumentation and scientific capability, but with no inherent limit of either velocity change or duration of propulsive operation.

Such a probe vehicle could be launched to low earth orbit by a less powerful conventional rocket vehicle at reduced expense, transferred to an orbit around an object of interest, and continue to be redirected to other such objects until some mishap ended the mission. Other applications of the method, such as the translation of satellites to geostationary orbit, station keeping and orientation, and their return to low earth orbit as desired for repair, salvage, or disposal could have a similar favorable economic impact.

Another use of immediate interest is the reboost of the International Space Station (ISS). Atmospheric drag (approximately 0.5 N during the period 2005-2008) requires the expenditure of some seven metric tons of rocket fuel at a cost of $120M each year to maintain the desired orbit. An engine utilizing the technology described above could provide this service while drawing power from the ISS solar electric arrays, and without the need for resupply.

A more distant application might be the combination of this method with a nuclear reactor thermal source as part of a Brayton cycle impeller section. Such a propulsion system may offer routine, rapid, and economic access to any location in the solar system for both manned and unmanned vehicles.

It is early days for this technology, and much interesting and rewarding work is yet to be done.

References

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