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14. ABSTRACT

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Analysis of Multi-Vane Radiometers in High-Altitude Propulsion

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A near-space propulsion system using radiometric forces is notionally developed for the Lockheed HALE-D vehicle. The purpose of the system is to provide wind disturbance compensation for the vehicle operation at 20 km. Experimental results indicate that using a multi-vane configuration increases the force produced per unit mass of the radiometer. Previous numerical studies were implemented to determine the force production of the proposed concept design. The proposed design features in integrated system where multi-vane radiometers line the surface of the vehicle and operate on solar power. The HALE-D vehicle at 20 km requires 40.1 billion sub-vanes, at 26 μm in length, covering a total area of 101 m^2 in order to produce the necessary 142.1 N of thrust to counter the wind drag. Results are also given for systems at altitudes above 20 km.

Nomenclature

h	=	convection coefficient [W/m^{2}K]
k	=	thermal conductivity [W/mK]
Kn	=	Knudsen number
L	=	radiometer vane height [m]
*L**	=	characteristic length [m]
λ	=	mean free path [m]
Nu	=	Nusselt number
Pr	=	Prandtl number
Re	=	Reynolds number
W	=	radiometer vane thickness [m]

I. Introduction

NEAR space is generally defined as the altitude region above where jet aircraft can produce enough lift to maintain level flight and below where stable orbital spacecraft can have reasonable lifetimes. Near space altitudes range from approximately 20 km to 100 km [1]. For near space vehicles to be useful, they must be able to loiter over a particular location for long durations, requiring the need for propulsion systems to compensate for drag due to stratospheric winds. A near space propulsion system using the radiometric force is investigated in this study. A thin vane immersed in a rarefied gas with a temperature gradient across its surfaces will produce a force that tends to move the vane from the hot side to the cold side [2]. This is the driving force of a Crookes radiometer, and hence,

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it is called the radiometric force. Recent studies [3, 4] have investigated radiometer configurations involving multi-vane arrays in an attempt to maximize the force produced per unit area (or mass). These numerical studies have shown that the force produced by multi-vane arrays is perhaps sufficient to be considered for application to a near space propulsion system.

A notional near space propulsion system designed to operate on radiometric forces is shown in Fig. 1. The propulsion system is designed to be conformal with a typical near space vehicle's outer structure. The radiometric engine is based on a multi-vane geometry powered by solar radiation. The radiometric force requires a temperature difference between two surfaces, where the force produced is a linear function of the temperature gradient [5]. To maximize the gradient, the hot surface and cold surface are separated by thermal insulator, in this case aerogel. The hot surface is designed to absorb solar radiation (absorptivity, $\propto\sim 1$) whereas the cold side is a reflector ($\propto\sim 0$). In this sense, the radiometric engine is solar driven; however, other designs can be envisioned where active heating of the hot surface (through power dissipation or Joule heating) is used.

The radiometric effect is most prominent in the rarefied transitional regime where the Knudsen number is between 0.01 and 10. The Knudsen number is defined as the ratio of the gas mean free path to a characteristic length in the flow.

$$Kn = \frac{\lambda}{L^*} \tag{1}$$

To date, interest in radiometric flows has been limited to micro-devices (i.e. small characteristic dimensions) in a high pressure environment. One of the most notable applications to radiometric flows is atomic force microscopy which has been brought to the forefront of modern nanotechnologies in the last several years [6]. However, based on Eq. (1), macro-scale applications in the low pressure regime (i.e. large mean free path with same equivalent Knudsen number) can also be envisioned, which is the basis for the near space propulsion system shown in Fig. 1.

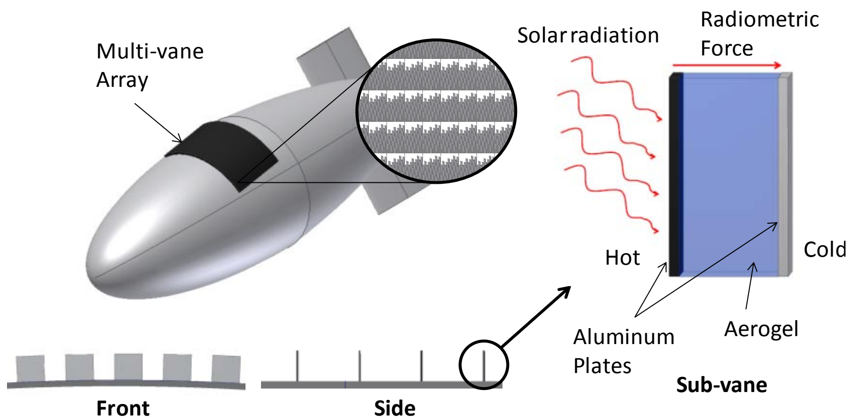

Figure 1: Radiometric propulsion system concept.

There are generally three major components to the force: (1) a pressure difference between the gas on the hot and cold sides (pressure force), (2) a force near the edge of the vane caused by non-uniform gas heating (edge force), and (3) a shear force due to thermal creep along the thickness of the vane (shear force). Molecules that impact the hot side have higher average velocities than those that strike the cold side; therefore, the direction of the pressure force is from hot to cold. In general, the shear force acts in the direction of cold to hot or in the opposite direction of the pressure force. Thus, the net force acting on the radiometer vane is a balance between the pressure and edge forces and the shear. Recent studies [7, 8] have shed significant light on the fundamental understanding of radiometric flows and the relative contributions of the area, edge and shear effects. These studies indicate that in the regime where the total radiometric force is maximized, the area and edge force contributions are on the same order of magnitude, suggesting that an optimal geometry can be created to maximize the total radiometric force by balancing these two force producing mechanisms. Designing a radiometric propulsion system for a near space vehicle requires optimizing the geometry of the vanes for maximum force.

This study seeks to experimentally verify the results obtained by the numerical studies [3, 4] that suggest that the radiometric force increases for multi-vane arrays over the same number of vanes operating independently. It also attempts to quantify the force per unit area that can be generated for near space propulsion. An integrated conceptual design is developed for a propulsion system to compensate wind disturbances on a generic near-space vehicle. This analysis used the Lockheed High Altitude Long Endurance Demonstrator (HALE-D) as an example system on which to base calculations. The HALE-D vehicle was developed for demonstration purposes as part of the DARPA ISIS program at a nominal altitude of 20km. The basic specifications for the HALE-D vehicle are shown in Table 1.

Table 1: Lockheed HALE-D Characteristics.

Characteristic	Value
Station-keeping Altitude	65000 ft
Payload weight	50 lbs
Hull Volume	500,000 ft^3
Length	240 ft
Diameter	70 ft

II. Experimental Setup

One way to increase the edge force on a radiometer vane while maintaining the surface area is to use a multi-vane configuration. Multi-vane radiometers provide more perimeter (and therefore more edge contribution) than single vanes with the same area (mass). An experimental analysis was conducted to determine the impact of using a multi-vane configuration as opposed to a single vane with the same active surface area. The impact of separation distance on the maximum force produced as well as chamber wall proximity was also investigated.

The experiment consists of three 40 x 40 x 3.5 mm thick Peltier thermoelectric cooler (TEC) modules acting as the radiometer vanes. A TEC is a solid state heat pump that operates on the Peltier effect. An array of p- and n-type semiconductors are connected in series and sandwiched between two ceramic plates. Applying a DC power through the module drives a temperature difference between the two ceramic plates. The use of TEC's allows the temperature difference to be actively controlled based on the power input. For this experiment, the temperature difference was maintained at approximately 25 K.

Previous experimental studies [5] have indicated that the wall proximity of the surrounding chamber plays a prominent role in radiometric force production. As a result, two different chamber sizes were studied. The radiometer vanes were initially inserted into a 1 m diameter vacuum chamber where the pressure was varied from 0.2 to 2.0 Pa (corresponding to a Knudsen number from 0.7 to 0.07 based on the size of an individual vane). This setup represents the large chamber configuration in the analysis. For the small chamber case, the vanes were inserted into a 32 x 16 x 12 cm aluminum box within the large chamber. Figure 2 shows a schematic of the experimental setup for the small chamber case.

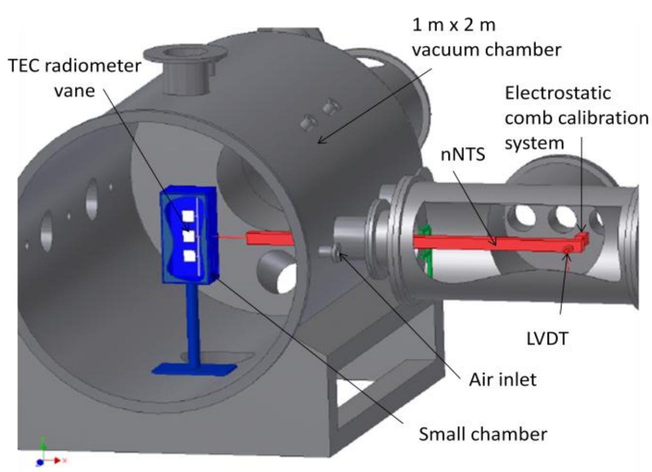

Figure 2: Experimental setup schematic.

The radiometer setup was mounted to a nano-Newton thrust stand (nNTS) [9] and centered in the chamber to achieve axial symmetry. The stand for this experiment generally had a standard deviation of less than 1% and a resolution of 800 nN. The nNTS was calibrated with electrostatic combs [10] before each set of data. A typical nNTS force trace is shown in Fig. 3a. The chamber is initially pumped to 10^{-4} Pa, where the force on the vanes is negligible. Air was then introduced into the chamber where it was allowed to reach a steady state pressure. A typical pressure profile for the chamber is shown in Fig. 3b. Once a steady pressure was reached, the deflection of the thrust stand was measured, yielding the force produced by the vanes. Finally the chamber was then pumped back to 10^{-4} Pa to re-establish a zero force reading.

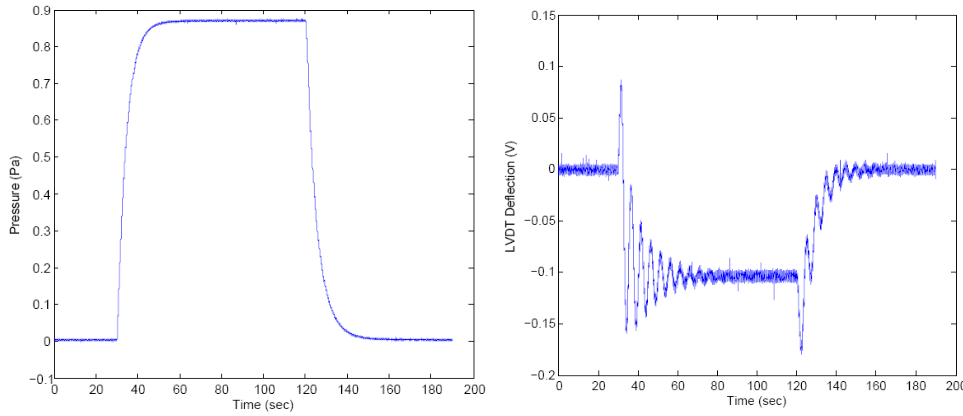

Figure 3: (a) typical pressure profile for measurement (b) typical nNST trace.

The single vane reference for the experiment was created by aligning three vanes with no gap separation. This setup was mounted to the stand and the maximum force was found. The vanes were then separated at varying distances ranging from 10% to 120% of the sub-vane height. Again, the maximum force was found for the multi-vane cases. By separating the vanes, the perimeter of the system increased by 50%; therefore, an increase in force production for the multi-vane configurations was expected due to an increase in edge force contribution. Finally, the single vane setup was compared to a two-vane configuration with 100% gap distance which represents etching a 4 cm hole in the single vane. Although the total force is expected to decrease by "etching" the hole, the force per mass is expected to increase.

III. Numerical Technique

A finite volume solver SMOKE [11] has been used to deterministically solve the ellipsoidal statistical kinetic equation [12]. SMOKE is a parallel code based on conservative numerical schemes developed by Mieussens [13]. The code can provide solutions for both two-dimensional and axisymmetric flows. A second order, spatial discretization was used with implicit time integration. Fully diffuse reflection with complete energy accommodation was applied at all radiometer and surrounding chamber surfaces. The lower boundary was set as the symmetry plane. Multiple radiometer vanes in a linear array were studied at various separation distances. The height of the radiometer vane was taken to be 1.1mm, and the vane thickness was set at 0.011mm. For the 2-D simulations, the length dimension for the radiometer vanes was infinite. The temperature of the hot side of the radiometer vane was set to 450K and the cold side was set to 410K. Argon was used as the working gas at pressures ranging from 20 to 6,000 Pa. Simulations were run for a surrounding chamber with dimensions of 0.495mm by 1.65mm wide with the chamber walls at a set temperature of 300K.

Grid convergence was achieved by increasing the number of spatial nodes and points in velocity space. The latter was (18,18,12) for the results presented in this study. The number of spatial cells varied from 5,000 to 50,000 depending on the size of the surrounding chamber. The temporal convergence was also controlled, and the total error in the force calculations was estimated to be less than one percent in all cases. The qualitative results will not change for different temperature gradient or radiometer size provided that the Knudsen numbers do not change. This implies that the results will be the same for a 10 times larger radiometer vane in a 10 times more rarefied carrier gas.

IV. Results

A. Experimental

Figure 4a represents the net radiometric force as a function of pressure for the single vane setup (0% separation) as well as for 30%, 70% and 110% separation for the large chamber setup. Note that as the separation increases, the maximum force increases. As shown in the figure, the 110% separation case produces approximately 25% more force at its maximum than the single vane. Also noteworthy in Fig. 4a is the change in location of maximum force. In separating the vanes from no gap to 110% gap, the pressure at which the maximum force occurred shifted from 0.85 Pa to 1.09 Pa. The shift is in large due the characteristic length changing from three times the length of a TEC (12 cm) to approaching the length of a single TEC (4 cm). Figure 4b shows the maximum force as a function of relative separation distance. As shown in the figure, the general trend indicates that the maximum force asymptotes to approximately 22.2 μN. Note that at separations above 90%, the data somewhat erratic. This variation in data is most likely caused by inconsistencies in the thrust stand measurements. Separating the vanes more than 90% caused the radial arm to shorten enough to cause an imbalance between arms and thus interfere with the measurements.

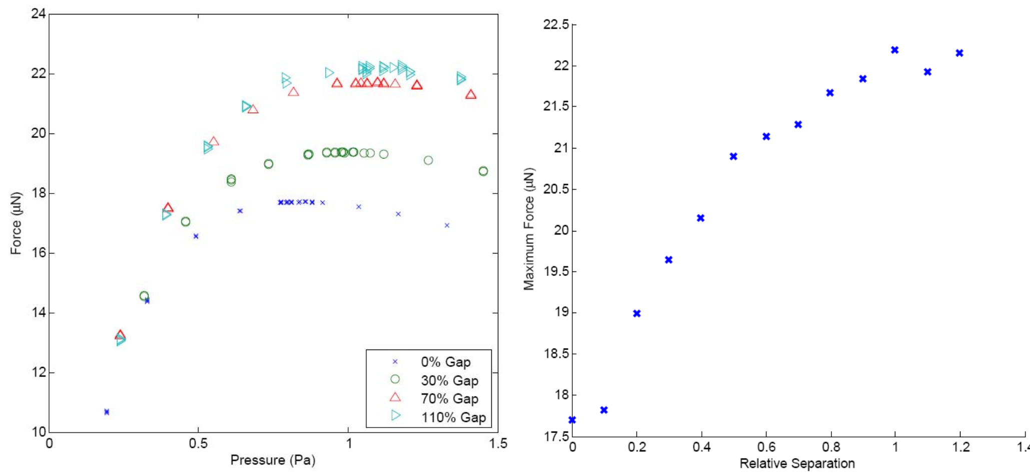

Figure 4: (a) Force as function of pressure for varying gap distances (b) Maximum force versus separation.

Figure 5 shows a comparison between the large chamber and the small chamber configurations. The force production increase from the large chamber to small chamber is a factor of approximately 2.5 as depicted in Fig. 5a

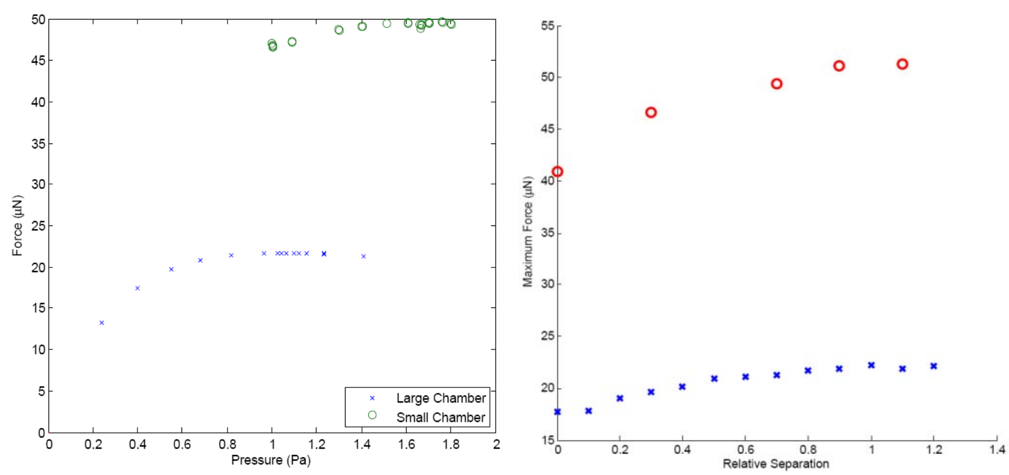

Figure 5: (a) 70% gap separation in large and small chambers (b) Maximum for versus separation distance for large and small chambers.

which represents the force for a given pressure for a 70% gap separation. The pressure at the maximum force is shifted from 1.05 Pa to 1.70 Pa indicating that the characteristic length of the system is somewhat dependent on the chamber wall proximity. The general asymptotic trend is maintained with the small chamber as shown in Fig. 5b.

Finally, Fig. 6 shows the force curve for the single vane compared to the etched hole configurations. As expected, the total force produced decreases with the presence of the hole. The total mass, however, for the two-vane case is 2/3 the mass of the single vane. Consequently, the two-vane configuration produces 17.8% more force per radiometer mass than the single vane. These results validate the principle behind using multi-vane radiometers for the proposed propulsion system.

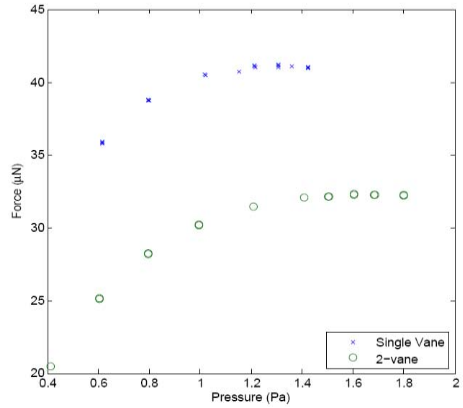

Figure 6: Total force for single and two-vane configurations.

A. Numerical Results

The numerical model was used to analyze the feasibility of increasing the radiometric force by etching holes in the vane creating a larger number of sub-vanes in the same total area originally occupied by a single large vane. The separation distance between sub-vanes is varied by changing the number of sub-vanes to find the maximum radiometric force produced. Fig. 7a shows the radiometric force produced as a function of operating pressure (or Kn) for the small chamber case. Since the effects of the shear force can be reduced by making thinner vanes or by changing the edge geometry [4], only the pressure force terms are shown in Fig. 7a. As the number of vanes increases, the separation between them correspondingly decreases for the same fixed radiometer area. As shown in Fig. 7a, the radiometric force significantly increases as the separation between the vanes decreases or as the number

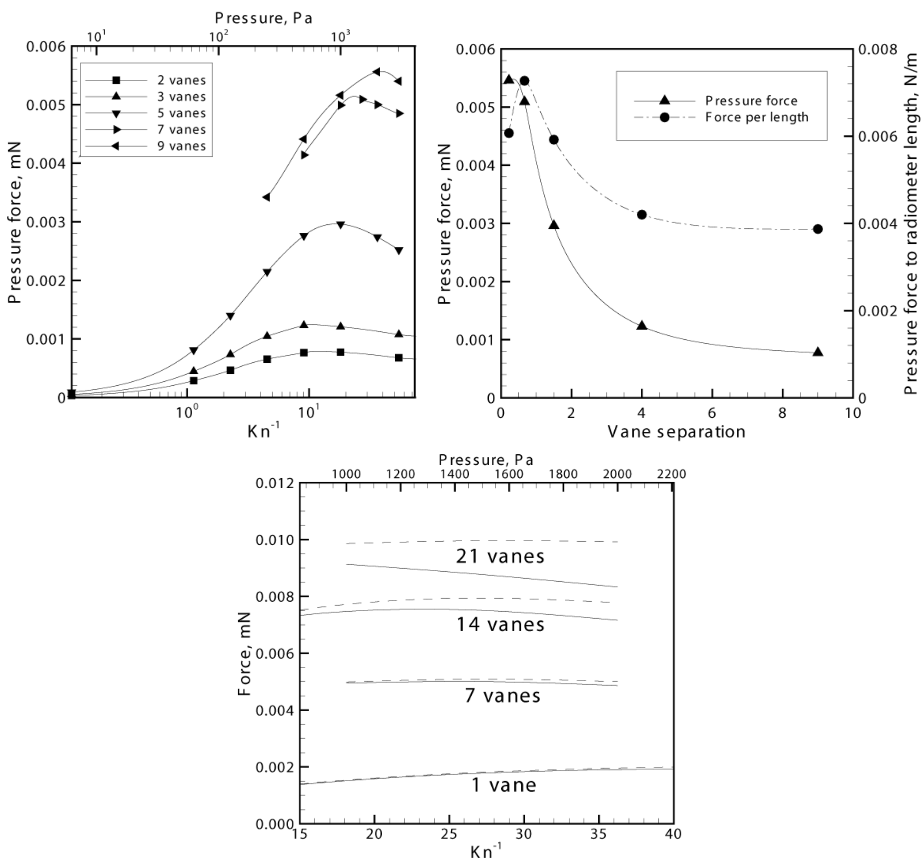

Figure 7: (a)Radiometric force for various multi-vane configurations (b) Total force and force production versus vane separation (c) Shear effects for multi-vane configurations.

of sub-vanes increases. The optimum separation distance was found to be approximately 0.75 times the length of a sub-vane as shown in Fig. 7b. In the limiting case of zero separation (i.e. a single, large radiometer vane), the radiometer force was found to be only about one-third of the maximum. Fig. 7c shows results as a function of the number of vanes in the same radiometer area keeping the vane separation distance constant at 0.75 times the length of the sub-vanes. There is an operational Kn for which the radiometric force maximizes. At a fixed pressure, the Kn for maximum force production can be obtained by changing the characteristic size of the vane. In Fig. 7c, the dashed lines show only the pressure force component and the solid lines shown the total force including shear. As the amount of perimeter of the radiometer increases with the number of sub-vanes, the shear force becomes increasingly important. As mentioned earlier, the shear force acts to decrease the total force by acting in the direction opposite of the pressure force. Ultimately, the shear force will limit the total number of sub-vanes that will produce a maximum force. A diminishing return is already seen between the total force produced by a 14 sub-vane radiometer and a 21 sub-vane radiometer in Fig. 7c.

In real engineering applications, the sub-vane characteristic length-to-thickness ratio (L/W) will not always be small. Numerical results were obtained for a 10 cm characteristic length with various vane thicknesses of 0.5, 1.0, and 1.5 cm. Table 2 shows the results for the pressure force, shear, and total force produced by a 7 sub-vane configuration for an operating gas pressure of 1.5 Pa that maximizes the total force produced. From these results, the total radiometric force decreases by approximately 7% between the thinnest and thickest sub-vanes due to the increase in shear. The numerical results presented in Table 2 are modified and used in subsequent sections to predict the force per unit area of a near space radiometric propulsion system. The results are modified in predictable ways based on experimental results [5] to account for differences in the temperature gradients, radiometer characteristic size and thickness, and operating gas (air instead of argon).

Table 2: Pressure, shear, and total radiometric forces

Configuration	W = 0.5 cm L/W = 20	W = 1.0 cm L/W = 10	W = 1.5 cm L/W = 6.67
F_p (N)	5.090×10^{-3}	4.948×10^{-3}	4.806×10^{-3}
F_s (N)	-8.560×10^{-5}	-1.148×10^{-4}	-1.312×10^{-4}
F_{tot} (N)	5.004×10^{-3}	4.833×10^{-3}	4.675×10^{-3}

V. Propulsion System Design

As stated above, the purpose of this analysis is to develop a propulsion system concept design which utilizes radiometric forces to compensate for wind disturbances. The design proposed in this manuscript features an integrated radiometric propulsion system for a generic near-space vehicle. The system, however, is altitude specific as the size of the individual vanes are dictated by the Knudsen number (pressure) in order to achieve the maximum force from the radiometer vanes. Here, the Lockheed HALE-D vehicle is considered, which operates at an altitude of approximately 20 km (corresponding to a pressure of 5.7 kPa). The nominal design, therefore, will compensate for wind drag on the HALE-D operating at 20 km. Using the information in Table 1 above and an average wind speed of 10 m/s [1], the force of wind drag on the vehicle is estimated at 142.4 N. The drag coefficient for this calculation was conservatively set at 0.1 for the streamlined airship. The radiometer array, therefore, is designed to completely compensate for the wind drag while minimizing the mass added to the vehicle.

In order to translate the numerical results into a multi-vane propulsion system concept design, it was assumed that for a given Knudsen number and L/W ratio, the force production (force per unit active length), shown in Table 2, remains constant. Therefore, the force production for the proposed propulsion system is determined by extrapolating from the numeric results for the design L/W ratio. The Knudsen number is assumed to be the same for both the numeric computations as well as the design i.e. the Knudsen number for maximum force (Kn = 0.03). In the numerical analysis, the total force is normalized by the active length for the seven vane setup (total physical surface length) to obtain the force production. Extrapolating from the numeric results yields the force production at the design L/W. The force production is then multiplied by the design active length to determine the total force produced on a multi-vane.

In order to accurately relate the numerical analysis to the concept design parameters, corrections for the operating gas in the numerical simulations as well as the varying temperature differences must be accounted for. Experimental studies have shown that a radiometer submersed in air produces about 90.3% of the force it would if submersed in argon. The same studies have also shown that the force produced by the vane increases linearly with temperature difference [5]. Therefore, all force production calculations are adjusted accordingly.

A. Design Concept

The design layout consists of several sets of multi-vane radiometers each of which features individual vanes lined end to end as shown in Fig. 1. These multi-vane sets are cascaded along the surface of the vehicle forming a radiometric mult-vane array. The length and depth of the multi-vanes are vehicle specific base on altitude. Each individual vane consists of silicone aerogel sandwiched between two thin aluminum plates. One aluminum plates is blackened to absorb the sunlight and act as the hot side of the radiometer. The other plate is polished in order to reflect sunlight. The temperature difference across the vane, therefore, is driven by the thickness of the aerogel and the convection from the wind. Aerogel can be manufactured with various densities and thermal conductivies; for the purposes of this design, a density of 100 kg/m^3 and thermal conductivity of 0.017 W/mK is used. To compensate for wind disturbance, therefore, the blackened side of the vane will face opposite the side facing the wind. A nominal case where the vehicle faces a headwind (thus the blackened sides face the rear of the vehicle) is considered. The distance between each multi-vane set is set at a factor of 2.2 times the height of an individual vane to coincide with the numerical results for the small chamber domain. Therefore, each of the multi-vanes acts as the chamber wall for the immediate surrounding vane. It is assumed that the circulation vortices on a particular vane are small enough as to not be influenced by the circulation of the neighboring vane.

The Knudsen number in which results in the maximum force production for a multi-vane setup, is 0.03 [3] and will determine the height of the individual small vanes. The atmospheric pressure and mean free path at 20 km is approximately 5.7 kPa and 781 nm respectively which fixes the individual vane size at 26.0 μm. The thickness of the vanes drives the temperature difference that can be achieved for the system. However, the L/W ratio places a limitation on the maximum thickness for the sub-vanes. As L/W decreases below unity, the shear forces acting in the opposite direction of the radiometric force become significant and cause difficulty in determining the multi-vane force production. Therefore, the proposed design shall not contain an L/W ratio below one for the individual vanes.

The temperature difference across the surfaces of the vanes can be estimated using a simple thermal resistance analysis with conduction through the Aerogel and convection on each surface of the vane. It is assumed that the blackened side of the vane entirely absorbs solar power (taken here to be 1200 W/m^2) and the polished surface complete reflects it. A rough order-of-magnitude approximation for the convection coefficient can be determined relationships for air flow over a flat plate.

$$Nu \cong 0.664\, Re^{1/2} Pr^{1/3} \quad (2)$$

and

$$h = \frac{Nu\, k_{air}}{L} \quad (3)$$

For air at 20 km, the Prandtl number is 0.720, the thermal conductivity is 22.3 x 10^{-3} W/mK, and the kinematic viscosity is 2.03 x 10^{-4} m^2/s. For a 26 μm vane, the convection coefficient is approximated as 706 W/m^{2}K. Although this scenario is does not necessarily represent flow over a flat plate exactly, the calculations should give a rough approximation sufficient for the design. The resulting temperature difference across the vane is 0.64 K.

B. HALE-D Design

The force produced by each multi-vane set is evaluated using the numerical results. The total length of each multi-vane is nominally set at 1 m. The results for a single multi-vane are then multiplied by the number of sets is a 1 m x 1 m area to obtain the total force per radiometer array area. The method used to extrapolate the total force was based on the numerical results from Ref. 4. As stated above, the multi-vane gap distance was set at 70% of the individual vane height. It is assumed that for a given L/W, Knudsen number, and gap distance, the force production (total force per unit active length) remains constant. From the numeric results, the force production for L/W = 1 is approximately 136 μN/m. The active area for the proposed system is 0.59 m for a 1 m long multi-vane with a 70% gap distance; hence, each multi-vane produces 80.3 x μN of total force. A 1 m square section contains 17480 multi-vanes spaced 57.2 μm apart. Therefore, the force per array area for the proposed system operating at 20 km is 1.4 N/m^2. To produce the necessary 142.4 N required for drag compensation on the HALE-D, the current design must contain over 40.1 billion sub-vanes and occupy 101 m^2. The total mass of the radiometer array is found by assuming each sub-vane consists of two very thin square aluminum plates on either side of the aerogel medium and, for the current design, is estimated at 14.7 kg. The resulting system occupies less than 1% of the total surface area of the vehicle while adding negligible mass.

Although the current concept design for the HALE-D vehicle meets the size and force requirements (according to the numeric results) necessary for head wind drag compensation, several issues exist that hinder the possibility of a radiometric propulsion system for this particular vehicle. The most notable issues that arise are the small temperature differences and sizes of each of the sub-vanes. Ideally, the temperature difference across the sub-vanes would be at least 20 K in order to obtain a reasonable force production from the multi-vane. Decreasing the temperature difference significantly decreases the force production. As a result, more vanes are needed, covering a larger surface area, to produce the necessary drag compensation. The second issue, involving small vane size (micro-scale vanes), poses problems not only in manufacturing the multi-vanes but also in the attachment to the vehicle. Combined with the sheer number of vanes required for the system (over 40 billion), the micro-scale vanes would be costly to implement. Increasing the size of the individual vanes both increases the practicality of manufacturing the system and allows for a greater achievable temperature difference for an L/W ≥ 1. The only means of increasing the individual vane size while still maintaining a Knudsen number of 0.03 (an therefore maximizing force per vane mass) is by operating at lower pressures i.e. higher altitudes. The design results for a 30 km system are shown in Table 3. The force of wind drag on the vehicle was estimated by scaling the HALE-D to operate at 30 km where the aspect ratio of the vehicle remains the same. Assuming that a fill density of 0.005 kg/m^3 could be achieved, the diameter of the new vehicle diameter increases to 37.7 m. The average wind speed at 30 km is 15 m/s [1] causing the drag force to be 216.0 N.

Although operating at 30 km instead of 20 km increases the achievable temperature difference from 0.64 K to 2.7 K, the individual vanes are still on the micro-scale and pose the same issues as the 20 km design. Therefore, a further increase in operating altitude is needed in order for the radiometer concept design to be plausible.

Table 3: Results for 30 km airship

30 km Engine Parameter	Result	Propulsion System Parameter	Result
Temperature Difference (K)	2.69	**Vehicle diameter (m)**	37.7
Force Production (μN/m)	574	**Wind speed (m/s)**	15
Sub-vane height (μm)	119	**Drag force (N)**	216
L/W	1	**Total array area (m^2)**	168
Force per multi-vane (μN)	337	**Total number of vanes**	3.16 x 10^9
Number of multi-vanes	3811	**Total array mass (kg)**	24.8
Force per array area (N/m^2)	1.29		
Number of vanes per area	1.88 x 10^7		
Mass per area (kg/m^2)	0.15		

C. High Altitude (> 30 km) Engine Design

Results for an altitude range of 40 to 80 km are shown in Table 4. For these results, a maximum temperature difference of 20 K was used if the resulting L/W ratio was greater than one. Since technology currently prohibits near-space vehicle from operating at these altitudes, generic results are given per unit area of the array and are not specific to any vehicle design. It is important to note that as the pressure decreases exponentially with increasing altitude, the vane size increases exponentially. At 80 km, the size each vane is 14.1 cm yielding an L/W ratio of 249 for 20 K temperature difference. As a result, the total number of vanes is a mere 15 vanes/m^2. Figure 8 shows the radiometric force per array area for an altitude range of 20 to 80 km. It is important to note that the systems operation in the 20 to 45 km range have L/W ratios of one resulting in temperature differences less than 20 K. The small size of the vanes also causes the convection to be more pronounced. Hence, the force per array area becomes more erratic with changing wind speeds as depicted in Fig. 8. Also noteworthy is that as the altitude increases, the force per area decreases exponentially, despite the increase in force production on each multi-vane from the increase in L/W. Consequently, the total area of the array must increase with altitude for a given total required force. Presumably, the vehicle size increases with altitude as well; therefore, the total area should not pose an issue.

Table 4: Results higher altitude engines.

Engine Parameter	40 km	50 km	60 km	70 km	80 km
Temperature Difference (K)	11.3	20	20	20	20
Force Production (mN/m)	2.41	4.57	4.96	5.42	5.94
Sub-vane height (mm)	0.52	1.90	6.12	26.0	141
L/W	1	2.73	10.0	45.1	249
Force per multi-vane (mN)	1.42	2.69	2.95	3.25	4.19
Number of multi-vanes	874	239	74	17	3
Force per array area (mN/m^2)	1240	644	218	55.2	12.6
Number of vanes per area	9.89 x 10^5	7.41 x 10^4	7180	391	15
Mass per area (kg/m^2)	0.16	0.16	0.16	0.16	0.17

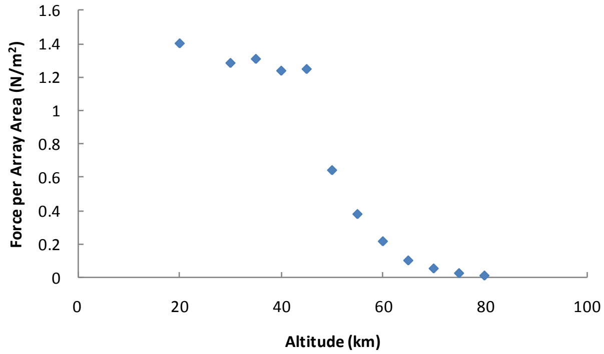

Figure 8: Engine design for an altitude range of 20 to 80 km.

VI. Conclusion

The focus of this paper was to develop a concept design in which utilized radiometric forces as a means to compensate for wind drag on a near-space vehicle. A multi-vane configuration was implemented to maximize the force production per unit mass of the system. An example system was designed for the Lockheed HALE-D vehicle which featured an array of multi-vanes integrated along the surface of the vehicle. All force production calculations were based on numerical studies for multi-vane radiometers. Issues with such a propulsion system arise due to the dependency on the sub-vane size with the operation altitude. Modern near-space vehicles have an operating limit at around 20 km. At this altitude, the individual vanes are on the micro-scale level. Although the proposed system for the Lockheed HALE-D vehicle could, in theory, produce sufficient force to compensate for wind drag at 20 km, manufacturing and implementation of the system could prove costly. This radiometric system is most viable at altitudes from 40 to 80 km where the size and number of vanes become more practical. Unfortunately, the technology to operate a near-space vehicle at those altitudes has yet to be realized.

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