Undergraduate Research Journal at UCCS
Volume 3.2, October 2010

Scaling Limitations of Micro Engines

Joseph C. P. Griebel
University of Colorado at Colorado Springs

Over the past decade, there has been a large push for the miniaturization of internal combustion engines. This is largely due to the relatively high energy density of hydrocarbons, which tend to be the preferred energy source of these engine types. This paper covers the multitude of scaling issues that remain prevalent in micro engine development, specifically focusing on engine displacements in the order of one cubic centimeter. The paper reviews obstacles caused by the disproportionate increase in the ratio of surface area to volume, including excess heat transfer as well as tribological factors. Issues caused by increased operational speeds are also addressed with special consideration given to residence and reaction time inequities. The fabrication limitations of these engines are also considered. Possible solutions to these scaling issues as well as promising applications are briefly discussed.

Nomenclature

$\zeta = intake\ parameters$
$r = stroke - to - bore\ aspect\ ratio$
$n = engine\ speed$
$V = chamber\ volume$
$P = chamber\ pressure$
$\dot{m} = mass\ flow\ rate$
$T = temperature$
$R = gas\ constant$
$\rho = density$
$\tau_{Residence} = residence\ time$
$\tau_{Reaction} = reaction\ time$
$LHV = lower\ heat\ value$

1. Background

Over the past few decades, the growing trend across a multitude of fields has been the miniaturization of products, components, and materials. This trend has persisted in the fields of technology, communications, and entertainment. Each discipline faces unique scaling issues.

Over the past decade, there has been a larger push for the miniaturization of internal combustion engines. This is largely due to the relatively high energy density of hydrocarbons, which tend to be the preferred energy source of these engine types. These small-scaled engines, termed “micro engines,” may contribute greatly to the advancement of miniaturization in other fields. Possible applications of these engines include a higher energy density alternative to battery power and a portable energy source for soldiers, campers, and backpackers, as well as a compact source of astrodynamic propulsion. However, unlike many disciplines, the miniaturization of engines is not as straightforward as merely scaling down individual components to create a universally scaled product.

Due largely to the unique thermodynamic properties of engine cycles, micro engines face many scaling issues. A primary concern in engine scaling is related directly to the square-cube law. This law states that when an object undergoes a proportional decrease in size, its new volume is inversely proportional to the cube of the multiplier, and its new surface area is inversely proportional to the square of the multiplier. Certain thermodynamic principles such as heat transfer and friction are dependent on the surface area of the combustion chamber; however, properties such as power output and efficiency are largely related to the volume of the chamber. When an engine is scaled down, the surface area increases inversely proportional to the volume of the chamber. This simple relationship has proven to produce numerous complications in the development of micro engines. For instance, the increased surface area leads to a disproportionate heat loss in the cycle. This relative increase in heat transfer can contribute to flame quenching and output losses. In addition, the associated power output of the engine is decreased significantly due to the disproportionate decrease in volume of the combustion chamber. In order to obtain useable power outputs, the engine speed must be increased to compensate for the loss in power per cycle. With this increase in cycle speed, surface friction, which is related to the surface area, quickly becomes a limiting factor in the scaling of micro engines.

In addition to the complications related to the volume and surface area relationships, there are further scaling issues involved in the creation of micro engines. The sheer miniscule nature of the dimensions presents further complications in friction, sealing, and fabrication limitations. As an engine approaches displacement values in the cubic centimeter range, it becomes increasingly difficult to incorporate the proper sealing, lining, and insulation necessary in a typical internal combustion engine. While a large-scale engine contains sealing rings within the combustion chamber, the minute dimensions of many micro engines does not allow for such design decisions. For this reason, a radial gap between the piston and cylinder walls exists in many micro engine designs. This leads to mass leakage and incomplete combustion processes. Many other liners and insulators cannot be scaled down properly due to fabrication limitations. This complication leads to further heat transfer and additional heat losses.

The limited volume of the combustion chambers in micro engines presents perhaps the most difficult complication. The effect the limited volume has on engine speed has already been addressed. However, with this increased engine speed, a timing issue arises. Since a micro engine typically must operate at speeds in the range of ten times its standard-sized counterpart,

ignition timing becomes a limiting factor. This timing aspect, in combination with an inadequate residence time within the chamber, leads to further losses due to incomplete combustion.
It is clear that the properties of the internal combustion process must be fundamentally reexamined in order for the ambitious goals of micro engine research and development to be realized.

2. Application

Micro engine technology may serve to be very useful across a multitude of disciplines. There is an increasing demand for a compact energy source that exhibits a relatively high energy density and can operate autonomously. Current battery technology exhibits energy density limitations of about 0.6 kJ/g for alkaline cells and 1.2 kJ/g for lithium cells [1]. In contrast, hydrocarbons continue to offer the highest energy density that is easily and safely attainable, typically averaging 70 kJ/g [1]. For this reason, internal combustion engines fueled by hydrocarbons would appear to be the most effective power source whenever severe size and weight limitations exist.

2.1. Personal Power

One major category of potential micro engine application is in the field of personal power systems. This category is comprised of devices that benefit a sole person on a limited power level. Examples of this application include an individual power source for soldiers, backpackers, and campers. Autonomous, mobile robotic devices used in deep sea and cave exploration, as well as military bomb squads, fall within this group as well. Developing improvements in the medical field such as artificial organs and mechanical exoskeletons used for rehabilitation could also benefit from developments in micro engine technology. These specific examples require a compact energy source that provides a significant power-to-weight ratio. Specifically, these power systems require power densities ranging from 10 to 1000 W/kg and energy densities from 500 to 5000 Wh/kg [2]. Densities of this order can simply not be achieved by current battery technology. In addition, the majority of these systems require a cycle life and autonomy that cannot be provided by current compact energy storage devices.

2.2. Aerospace Applications

Another promising application lies in the field of aerospace technology. Recent NASA initiatives envision future aircraft to be intelligent, highly efficient, and virtually inaudible [3]. For this reason, there has been a recent push away from the wing-mounted and fuselage-mounted engine configurations currently used to an innovative vector propulsion concept. This concept revolves around the basic principle of replacing a few large jet engines with numerous smaller-scaled engine propulsion systems. Although current micro engine limitations render these engines much less efficient than their large-scale counterparts, the benefits associated with noise and drag reduction in combination with a decrease in replacement costs may very well outweigh the individual efficiency limitations. Additionally, the lack of singular engine dependence would enhance aviation safety in light of the fact that multiple engines could compensate for singular engine failure. This is an advantage that is not possible with current engine configurations. At the very least, the noise reduction factor and high thrust-to-weight ratios could enable micro engine application to be beneficial in short-term lift operations [4].

2.3. Electronic Applications

On perhaps an even smaller scale, micro engine developments could serve useful in numerous types of portable electronic devices. The increased energy density of hydrocarbons in comparison to the battery cells currently used make micro engines an attractive alternative. Many of these devices operate in the order of just ten watts, largely avoiding the power output limitations of these engines [4]. In addition, a small-scaled internal combustion engine would simply require fuel cartridge replacements, a much less debilitating obstacle than the battery life impediments that currently plague the technological advancement of electronic devices.

3. Scaling Issues

3.1. Square Cube Law

As mentioned previously, one of the most prevalent scaling issues deals directly with the proportionality that exists between the volume of an engine and its surface area. The square cube law states that, when an object undergoes a proportional decrease in size, its new volume is inversely proportional to the cube of the sizing factor, and its new surface area is inversely proportional to the square of the sizing factor. For this reason, the ratio relating surface area to volume becomes increasingly disproportionate as the overall size of the engine is decreased. This phenomenon is illustrated in Figure 1.

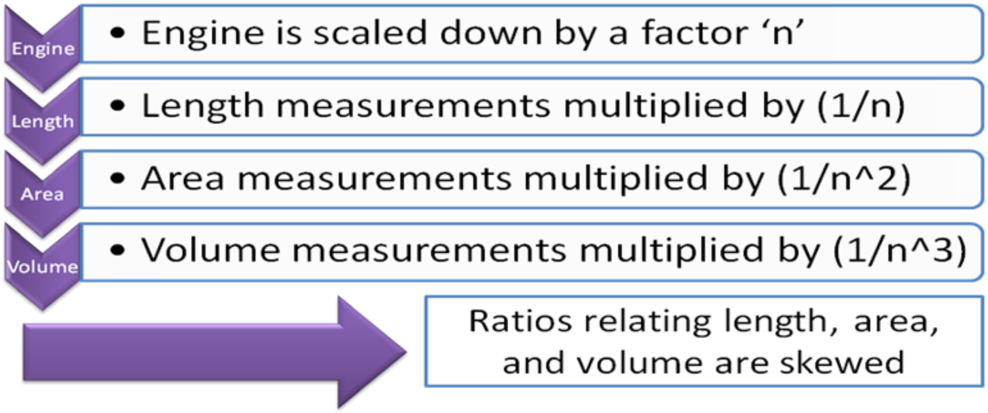

Figure 1: Square Cube Law Illustration

3.1.1. Tribology Factors

One major area of concern associated with this scaling issue is the increased role tribology plays in engine performance. The inner surface area of the piston cylinder does not decrease linearly with the change in overall cylinder volume. For this reason, the friction, wear, and stiction factors within the cylinder become controlling factors much sooner than that of a standard-sized engine. In order for these engines to perform properly, all of these issues must be simultaneously addressed. However, this dilemma does not have a simple solution. A fundamental dilemma in the design considerations revolves around the question of whether to allow for a greater friction factor or a greater percentage of mass loss within the control volume. Due to the inability to incorporate sealing rings in many design schemes, friction losses are almost unavoidable in order to limit the risk of extensive chamber leakages. In addition, stiction factors generally prevent the use of boundary lubrication in micro engines [5]. This restriction makes friction and wear factors essentially inevitable. Obviously, these factors can cause serious complications. In extreme cases, the dry friction rub impact that is created can cause the systems as a whole to experience resonance and even instability [6]. In order to alleviate these hindrances, significant research has occurred in the development and analysis of different types of thin films that could create considerably lower friction and wear surfaces. Testing and analysis performed by Rha, et al. on carbon films produced results with friction coefficients as low as .05, wear coefficients in the order of 10^{-8}, and a water contact angle exceeding 85°. Films of this nature appear to meet the necessary requirements to reduce all factors within the tribological phenomenon and could prove useful in further micro engine development.

3.1.2. Heat Transfer

The second issue that arises with a disproportionate increase in surface area is the resulting increase in heat loss to the surroundings. This occurs because power output and, consequently, heat generation are related directly to engine displacement volume, while heat rejection is related directly to the chamber surface area. Although significant heat transfer is often considered a beneficial effect when modeling large-scale engines, this is not the case in the design of their micro-scale counterparts. As the engine scale decreases, the relative heat transfer increases exponentially. This can have drastic effects when considering internal combustion engines with displacements in the order of a cubic centimeter. The primary concern that presents itself is the loss of heat across the chamber wall during flame propagation. During the combustion process, as the flame travels along the chamber, heat is passively rejected through the chamber walls. In many cases, the ratio of surface area to volume within the chamber is substantial enough to lead to a phenomenon known as thermal quenching. This occurs when the magnitude of heat transfer is too immense for the combustion within the chamber to remain self-sustaining [7]. This leads to incomplete flame propagation and effectively decreases the extent to which energy contained within the fuel can be utilized. A theoretical model put forth by Lee and Kwon cited that flame quenching can lead to combustion efficiencies as low as 60% on a millimeter scale. This is compared to macro-scale efficiencies as high as 90% [8]. This procedural inefficiency can have a drastic effect on the total performance of the system. Although flame quenching can have a major impact on engine performance, it does not generally serve as a sole limiting factor [2]. It is estimated that flame quenching alone does not become a limiting factor until there is a .007 cubic centimeter displacement for methane-fueled systems and a .033 cubic centimeter displacement for propane-fueled systems [9]. However, the adverse effects that excess heat transfer and flame quenching have on efficiency present themselves long prior to the point at which they become a sole limiting factor. So, although heat loss during combustion is often negligible in typical combustion engines, it can considerably affect the overall thermal efficiency of micro engines.

3.2. Operating Speed

Clearly the disproportionate surface area presents obstacles, but the diminished relative volume of micro engines also presents several problems. The principal problem associated with the diminutive displacement volume is a lower power output. This is due to the direct relationship between engine power and the chamber swept volume. Since this value is being decreased disproportionately, design decisions must be made in order to compensate for this discrepancy in relative power. In most micro engine designs, the operating speed of the engine is increased to alleviate this problem and increase efficiency. The necessary engine speed requirements can vary widely and are largely based on the stroke-to-bore aspect ratio, pressure, temperature, and mixture composition [10]. Aichlmayr, et al., computed the necessary engine speed up to 12,000 Hz. The effect of pressure, temperature, and mixture were summed to create a singular intake parameter variable.

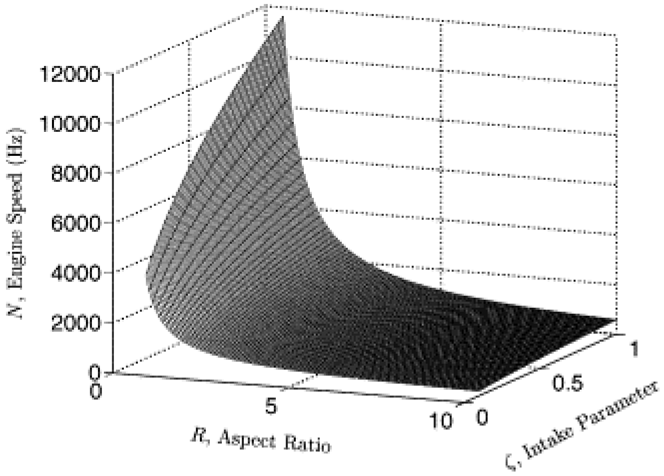

Figure 2: Engine Dependence on aspect ratio and intake conditions (Aichlmayr, et al).

Clearly, required engine speeds can increase greatly in accordance with these parameters. Specifically, Lee, et al. has put forth a Wankel engine design that requires engine speeds ranging from 2,500-18,000 rpm [11]. This engine operates on the Otto cycle and has a displacement of $63.5\ mm^3$. On an even smaller scale, an engine has been developed at the MIT laboratories that can reach operational speeds of 1.3 million rpm [4]. Although these two examples contain engine displacements that comprise the lower bound to which micro engine research is currently restricted, the effect is evident across all scales. That is, whenever engine displacement approaches the order of one cubic centimeter, engine speed must increase considerably to produce a useable power output.

3.2.1. Effect on Friction and Wear

This increase in operational speed creates numerous problems. Specifically, the increased speed further emphasizes the drastic effect friction, wear, and stiction factors play in limiting engine size and efficiency. These hindrances have already been extensively discussed and are only further stressed with the need for higher operational speeds. In extreme cases, the magnitude of friction losses can be on the same order as engine work output.

3.2.2. Effect on Residence Time

Furthermore, the elevated engine speeds also present obstacles involving residence time. Residence time is broadly defined as the duration of time a substance spends within a specified region of space. In terms of this application, the residence time within the combustion chamber can be approximated by the volume of the combustion chamber over the volumetric flow rate through the chamber [12]. This relationship is evident in equation (1).

$$\tau_{Residence} \approx \frac{Volume}{Volumetric\ Flow\ Rate} = \frac{VP}{RT\dot{m}} \tag{1}$$

Since the volume is so significantly decreased in micro engine design schemes, a correlating reduction in residence time is essentially inevitable. In order for complete combustion to occur, the residence time must always exceed the chemical reaction time of the fuel source. While this is rarely of concern in macro scale designs, it quickly becomes a limiting factor in micro engine designs. Unlike residence time, reaction time remains relatively constant with the change in relative volume. This is because reaction time is largely dependent on fuel properties and the mixture temperature and pressure [12]. For this reason, it is relatively difficult to ensure that the residence time always remains greater than the reaction time. This inequity limits flame propagation in spark-ignited systems and, therefore, limits combustion efficiency, which is already inhibited due to the aforementioned excess heat transfer across chamber walls.

3.2.3. Residence and Reaction Time Inequities

In order to avoid this phenomenon, design decisions must be made in order to either increase residence time or decrease reaction time. Since the chamber volume is the limiting factor in this case, it can be assumed to be constant. Therefore, referring back to the relationship presented in equation (1), the only way to increase the residence time within the chamber is to decrease the volumetric flow rate within the chamber. However, high-power density requirements demand a high mass flow rate through the chamber volume [12]. This fact is illustrated in equation (2).

$$Power\ density \propto \frac{LHV\dot{m}_f}{V} \propto \frac{\dot{m}\rho}{V\tau_{Reaction}} \tag{2}$$

Essentially, residence time cannot be reduced without having a detrimental impact on the power density. Since superior power density levels is the primary characteristic that initially established hydrocarbon fuels as an attractive alternative to chemical energy storage, a reduction in residence time seems accordingly impractical.

Reaction times are largely constant in relation to the volume change; therefore, the quest to improve the residence and reaction time inequities appears to be at an impasse. However, current research suggests that this is not the case. Although reaction time is largely unaffected by volume change, it can be varied by modifying material properties. One of these promising modifications includes the addition of catalytic substances within the chamber. The addition of a catalyst lowers activation energy and consequently increases reaction rate, while decreasing reaction time [12]. This approach is largely ineffective in macro scale designs due to the increasingly exothermic nature of the combustion process. The elevated reaction temperature due to the addition of a catalyst produces considerable excess heat, which cannot be easily dispensed in macro scale design. However, this effect is generally not a concern in micro engine designs since the excess heat is easily rejected due to the disproportionate surface area characteristic. It has been found that the addition of a platinum catalyst in hydrocarbon-fueled systems can produce overall efficiencies exceeding 40% [12]. These findings were found in designs where hydrocarbon combustion was not formerly possible due to insufficient flame propagation.

3.3. Fabrication Limitations

In addition to complications involving thermodynamic and chemical properties, micro engine development is also hampered by limitations that are purely associated with the fabrication of these miniscule engines. Current fabrication technologies are largely insufficient in meeting the demand for increasingly minute and detailed micro engine components.

3.3.1. Linings, Insulation, Sealing Rings

Certain aspects of macro-scaled engines simply cannot be incorporated into micro engine design. Some of these include cylinder linings and insulation. Even in macro scale design, these components are incredibly thin in comparison to other engine components. When the engine is scaled down, however, this relative size discrepancy is further emphasized, causing the fabrication of these components to be largely impractical. In the rare cases where current fabrication technology allows for the creation of these linings, the resulting decrease in malleability and increase in brittleness makes the installation of these components impractical. The lack of proper lining and insulation leads to further excess heat transfer, a process that already plagues micro engine design. In addition to lining and insulation, the miniscule nature of these machines generally prevents the use of sealing rings. This leads to improper sealing between the piston and cylinder wall, which produces considerable losses. These losses can become a limiting factor in many micro engine design schemes.

3.3.2. Piston-cylinder Gap

In many micro engine designs, a piston-cylinder gap is purposefully incorporated to avoid detrimental rub impact and friction effects [7]. However, due to the lack of sealing rings, special attention must be paid to limiting this gap. In illustration of this point, Sher, et al. produced a theoretical model constrained by an engine displacement of one cubic centimeter. At an operating speed of 24,000 revolutions per minute, a piston-wall gap of just 20 µm led to a mass loss of 58% (see Figure 3). At this mass loss percentage, the pressure created at the top dead center position is not sufficient for compression ignition. Even assuming theoretical combustion, the cycle produces an overall efficiency of just 15%.

Reducing this gap to 10 µm decreases the mass loss to 16% and increases the cycle efficiency to 54% (see Figure 4). These levels allow for compression ignition to be incorporated into the engine design and produce acceptable cycle efficiencies [7].

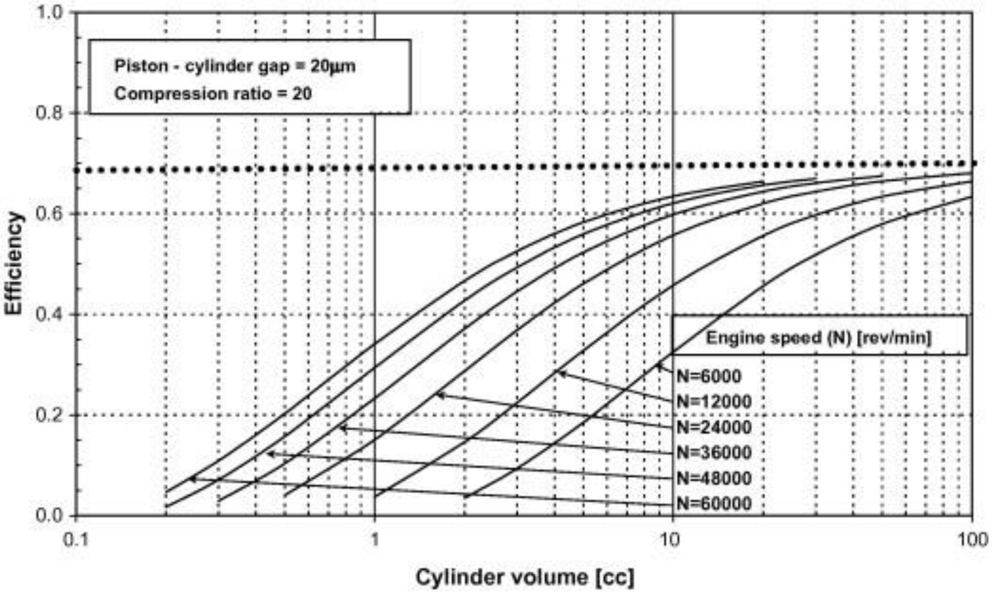

Figure 3: Efficiency vs. cylinder volume with 20 µm gap (Sher, et al.)

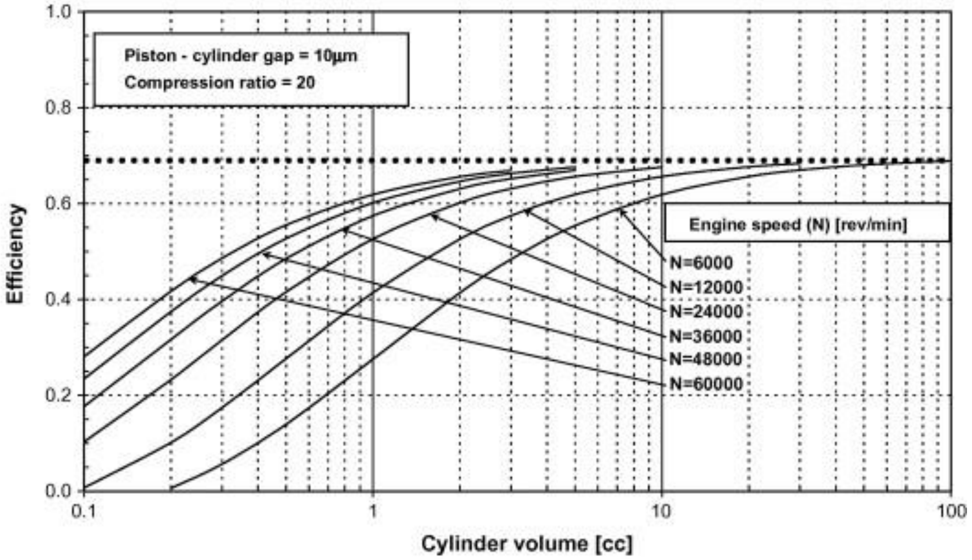

Figure 4: Efficiency vs. cylinder volume with 10 µm gap (Sher, et al.)

It is clear that the piston-cylinder gap, although necessary, can quickly become a limiting factor. At an engine speed of 24,000 revolutions per minute, a gap of just 20 µm produces a mass loss percentage that is too immense for compression ignition to take place [7]. The results presented by Sher, et al. suggest that decreasing this gap by 50% alleviates this problem and can improve the overall system efficiency by 39%. However, fabricating an engine with a 10 µm gap is still largely infeasible in practical applications. Current fabrication techniques limit the reduction of this gap and therefore constrain the cylinder volume in traditional piston-cylinder designs in order to obtain practicable mass loss percentages.

4. Conclusion

There are currently lofty aspirations related to the research, design, and development of internal combustion micro engines. The superior energy density of hydrocarbons, which tend to be the preferred fuel of these engine systems, offers a considerable advantage over chemical storage devices such as alkaline and lithium batteries. This overwhelming advantage suggests that micro engine application in the fields of personal power and electronic technology is very promising. Evolving performance and safety standards in the field of aerospace engineering also provide a promising future for the application of micro engines.

In order for these high aspirations to reach fulfillment in realistic application, several pertinent scaling issues must first be addressed. The disproportionate relationship that is formed between engine surface area and volume during the miniaturization process creates hindrances related to tribological factors and excess heat transfer. In order for useful power outputs to be obtained from these systems, the engine speeds of these models must be increased significantly. This substantial increase in operating speed further emphasizes the effects of friction, wear, and stiction. Additionally, these imposing engine speeds often result in residence and reaction time inequities, which hinder flame propagation and combustion efficiencies. Aside from thermodynamic limitations, micro engines also face limitations based solely on the fabrication of the engine components. Many essential engine components do not scale well and lead to further design constraints.

Current and continuing research in the field of micro engine development offers promising technological advancements that could lead to realistic and practical development and incorporation of micro-scaled internal combustion engines. These advancements include the possible incorporation of carbon films that effectively reduce tribology factors as well as the addition of intra-chamber catalysts that significantly reduce reaction time and combustion inefficiencies.

Further research, development, and prototyping must be completed in order to successfully alleviate these and other scaling issues and fully realize the ambitious goals and aspirations that surround micro engine development.

References

[1] Sher, I., Levinzon-Sher, D., Sher, E., 2009, “Miniaturization Limitations of HCCI Internal Combustion Engines”, Applied Thermal Engineering, **29**(2-3), pp. 400-411
[2] Dunn-Rankin, D., Leal, E.M., Walther, D.C., 2005, “Personal Power Systems”, Progress in Energy and Combustion Science, **31**(5-6), pp. 422-465
[3] Sehra, A.K., Whitlow Jr., W., 2004, “Propulsion and Power for 21st Century Aviation, Progress in Aerospace Sciences, **40**(4-5), pp. 199-235

[4] Epstein, A.H., Senturia, S.D., Al-Midani, O., et al., 1997, “Micro-Heat Engines, Gas Turbines and Rocket Engines—The MIT Microengine Project”, AIAA Paper 97-1773, *Twenty-Eighth AIAA Fluid Dynamics Conference*

[5] Rha, J.J., Kwon, S.C., Cho, J.R., Yim, S., Saka, N., 2005, “Creation of Ultra-low Friction and Wear Surfaces for Micro-devices Using Carbon Films”, Wear, **259**(1-6), *15th International Conference on Wear of Materials*, pp. 765-770

[6] Zhang, W., Meng, G., Chen, D., Zhou, J., Chen, J., 2008, “Nonlinear Dynamics of a Rub-impact Micro-rotor System with Scale-dependent Friction Model”, Journal of Sound and Vibration, **309**(3-5), pp. 756-777

[7] Sher, I., Levinzon-Sher, D., Sher, E., 2009, “Miniaturization Limitations of HCCI Internal Combustion Engines”, Applied Thermal Engineering, **29**(2-3), pp. 400-411

[8] Lee, D.H., Kwon, S., 2002, “Heat Transfer and Quenching Analysis of Combustion in a Micro Combustion Vessel”, Journal of Micromechanics and Microengineering, **12**(5), pp. 670-676

[9] Sher, E., Levinzon, D., 2005, “Scaling-down of Miniature Internal Combustion Engines: Limitations and Challenges”, International Journal of Heat Transfer Engineering, **26**(8), pp. 1-4

[10] Aichlmayr, H.T., Kittelson, D.B., Zachariah, M.R., 2002, “Miniature Free-piston Homogeneous Charge Compression Ignition Engine-compressor Concept--Part I: Performance Estimation and Design Considerations Unique to Small Dimensions”, Chemical Engineering Science, **57**(19), pp. 4161-4171

[11] Lee, C. H., Jiang, K.C., Jin, P., Prewett, P.D., 2004, “Design and Fabrication of a Micro Wankel Engine Using MEMS Technology”, Microelectronic Engineering, **73-74,** pp. 529-534

[12] Spadaccini, C.M., Zhang, X., Cadou, C.P., Miki, N., Waitz, I.A., 2003, “Preliminary Development of a Hydrocarbon-fueled Catalytic Micro-combustor”, Sensors and Actuators A: Physical, **103**(1-2), pp. 219-22