Exploring the Potential of Ionic Liquids for Enhanced Thermal Management in Spacecraft Systems

Jahnavi Sinha, Jacobo Ospina, Karen Morales, Inhae Lee
Cornell University, Ithaca, New York, 14850

Current challenges in spacecraft thermal management revolve around expanding the operational temperature range of heat pipes and the scarcity of safe, thermally stable working fluids. This paper proposes Ionic Liquids (ILs) as a new category of working fluid, suitable for intermediate to high temperatures. Their low volatility, excellent thermal and chemical stability, and customizability position them as potential "designer working fluids" which could emulate the properties of traditional fluids such as ammonia and water, but at elevated temperatures. Our research assesses the viability of using ionic liquids at higher temperatures, where the performance of conventional working fluids begin to decline. We investigate the operational limits of four ionic liquids, each representing different chemical groups and characteristics, within a sintered wick heat pipe setting. Additionally, we observe how altering heat pipe geometry impacts these operational limits. The performance of these ionic liquids is benchmarked against ammonia and water, demonstrating more favorable operational limits in most areas, with the exception of the viscous limit.

I. Nomenclature

r_v = Cross-sectional radius of vapor core
r_i = Inner container radius
l_e = Evaporation length of heat pipe
l_{ad} = Adiabatic length of heat pipe
l_c = Condensation length of heat pipe
l_t = Total length of heat pipe
l_{eff} = Effective length of heat pipe
A_v = Cross-sectional area of the vapor core
A_w = Wick cross-sectional area
λ_m = Thermal conductivity of heat pipe material
t = Temperature of Fluid Properties
ρ_v = Vapor density
d = Sphere Diameter
ϵ = Porosity
K = Wick Permeability
r_{eff} = Effective Radius of Capillary Structure
λ_{eff} = Effective Thermal Conductance
P_v = Vapor Pressure
P_c = Capillary Pressure
l_v = Latent Heat of Vaporization
μ_v = Vapor Viscosity

μ_l	=	Liquid Viscosity
σ_l	=	Surface tension of liquid
ρ_l	=	Liquid density
g	=	Acceleration due to Gravity
λ_l	=	Thermal Conductivity of Liquid
r_n	=	Nucleation Radius
θ	=	Contact Angle Fluid-Wick
ϕ	=	Axial Orientation
P_{vc}	=	Pressure of Vapor at Condenser
Q_c	=	Maximum Heat Transfer Rate due to Capillary Limitation
Q_v	=	Maximum Heat Transfer Rate due to Viscous Limitation
Q_s	=	Maximum Heat Transfer Rate due to Sonic Limitation
Q_e	=	Maximum Heat Transfer Rate due to Entrainment Limitation
Q_b	=	Maximum Heat Transfer Rate due to Boiling Limitation

II. Introduction

In the dynamic field of aerospace engineering, the quest for efficient and versatile thermal management solutions remains a persistent challenge. Ionic Liquids (ILs), a class of molten salts with unique properties, have garnered attention for their potential applications in various domains. Ionic liquids (ILs) constitute a distinctive class of molten salts that remain in a liquid state at relatively low temperatures, often below 100 degrees Celsius. Their unique properties stem from the combination of large, asymmetric organic cations and small, typically inorganic or organic anions, resulting in an ionic nature. Notably, ILs lack a defined melting point, allowing them to exist in a liquid state over a broad temperature range.

What sets ILs apart is their remarkable customizability—researchers can design ILs with specific properties by selecting different combinations of cations and anions, making them versatile for a wide range of applications. They exhibit low volatility, reducing the risk of vaporization during operation, and they often display high thermal stability, resisting decomposition or degradation at elevated temperatures. With a wide liquid temperature range, including room temperature and beyond, ILs find applications in fields such as green chemistry, electrochemistry, and catalysis. However, challenges such as cost, toxicity, and potential long-term effects still need to be addressed for widespread commercial adoption [1].

In the context of spacecraft technology, ILs offer several advantageous properties. Their ability to remain in a single, stable phase across a broad temperature range enhances the reliability of passive thermal control systems (TCS) in space. Compared to standard working fluids like water and ammonia, ILs exhibit significantly higher thermal conductivity. This characteristic is vital for efficient heat transfer in the extreme thermal environments encountered in space. Furthermore, the versatility in synthesizing ILs by varying cation and anion combinations allows for the creation of fluids with properties tailored to match or even surpass those of standard working fluids. This versatility opens up new possibilities for spacecraft design, particularly for thermal management systems operating in intermediate to high-temperature ranges. The extensive array of potential ionic liquid combinations represents a largely unexplored domain for customizable working fluids, presenting a frontier for innovation in spacecraft technology.

III. Literature Review

A. A Review of the Thermophysical Properties and Potential of Ionic Liquids for Thermal Applications.

The paper, "A Review of the Thermophysical Properties and Potential of Ionic Liquid for Thermal Applications", summarizes the general thermophysical properties of ionic liquids and how such characteristics can make them viable candidates as heat transfer fluid. Unique properties to consider with ionic liquids are their low vapor pressure, non-flammability, high chemical and thermal stability, and recyclability. These properties allow them to be used for a large range of applications. Many of these properties coincide with the necessary properties of any good working fluid, such as high thermal stability, low flammability, and low toxicity. What causes ionic liquids to stand out from other heat transfer fluids is its high thermal stability that allows it to operate at high temperature ranges easily. However, one of the aspects to be wary about ionic liquids is its high viscosity which can affect the fluid's pressure drop and needed pumping power. A positive to this though is that viewing ionic liquids at a higher temperature range can often result in a decrease in its viscosity. This is an insight into how ionic liquids could be a future possibility as a working fluid for far more extreme temperatures. In terms of density of ILs it can vary based on the type of liquid chosen, and it is minimally affected by temperature. The thermal conductivity of ILs as of the time of this paper do not have a definitive value or method of finding the property. Other drawbacks of ILs are the cost and corrosion risk it poses to surfaces.

This paper allows us to view in depth the properties of IL and how each one changes either due to the operating temperature or ionic structure of the liquid. This paper provides a good basis for our study on what properties of an ionic liquid may be a concern for heat transfer fluid application, such as viscosity or the difficulty of defining thermal conductivity for some ILs. The paper also advises what parameters of the ILs environment may be changed to offset unfavorable features, for example increasing temperature to decrease viscosity. This includes a brief discussion of chemical composition that helps steer our initial search for the right ionic liquid. The paper also underscores the scarcity of data on ILs' thermal conductivity and the influence of temperature and chemical structure on their thermophysical properties. While acknowledging the advantageous thermal and chemical stability of ILs, the paper points out challenges such as high costs and limited real-life application data. It concludes with a call for extensive research to fully characterize ILs and their potential in practical applications, highlighting their versatility and the need for experiments on more cost-effective synthesis methods [2].

B. A Review of Ionic Liquids, Their Limits and Applications

The paper, "A Review of Ionic Liquids, Their Limits and Applications" by Khashayar Ghandi, discusses the different categories of Ionic Liquids (ILs) and their applications. ILs are categorized into four types based on their cation segment: alkylammonium, phosphonium, dialkylimidazolium and N-alkylpyridinium cations. ILs can also be categorized into two types based on their hydrogen bondings: protic ILs (PILs) and aprotic ILs (APILs).

The alkylammonium-based ILs are an ammonium-based one. They have good electrochemical cathodic stabilities, low melting points and low viscosities. The dialkylimidazolium-based ILs are an imidazolium based, known as its stability within oxidative and reductive conditions, low viscosity and ease of synthesis. They are also good catalysts for the improvement of reaction time, yield and chemoselectivity of many organic reactions. The phosphonium based ILs are thermally stable compared to the alkylammonium and dialkylimidazolium based ILs and often used for CO_2 capture. The N-alkylpyridinium based ILs are a pyridinium based and work as great catalysts for the synthesis of some pharmaceutical agents such as 1,4-dihydropyridine, dihydropyrimidinones and 3,5-bis(dodecyloxycarbonyl)-1,4-dihydropyridine derivatives.

Despite there have been more studies on APILs than PILs, PILs have good potential for fuel cells. PILs tend to have higher conductivity and fluidity and lower melting points. Moreover, they are cheaper and convenient to synthesize. However, a hydrogen bond network of PILs limits their ionicity compared to APILs. PILs' defined proton activity and high proton conductivity make it easier to operate under non-humidified and high temperature conditions, which are beneficial for proton-conducting electrolytes for polymer membrane fuel cells. PILs are also non-corrosive, non-volatile and recyclable compared to mineral acids as well as a great catalyst in many microwave-assisted reactions. While studies have shown that PILs with larger proton transfer energies have weaker thermal stability, ILs with greater van der Waals interactions and hydrogen bonding have higher viscosity and ones with greater mobility, which means greater size of the cation, results in greater ion conductivity. The article emphasizes understanding of ILs for efficient use of materials [3].

C. Thermal and Transport Properties of Six Ionic Liquids: An Experimental and Molecular Dynamics Study

The paper "Thermal and Transport Properties of Six Ionic Liquids: An Experimental and Molecular Dynamics Study" analyzes [bmim][Pf2N], [bmim][Tf2N], [bmmim][Tf2N], [bmpyr][Tf2N], N-butyl-N, and Ntrimethylammonium bis[(trifluoromethyl)sulfonyl]imide. Specifically, it examines their density, heat capacity, self-diffusivity, viscosity, and thermal conductivity across a range of temperatures. What differentiates this paper compared to the others in our literature review is that they make use of molecular dynamics to create a model that is compared against experimental data. One of the primary motivations behind this research is to explore the viability of ILs as heat transfer fluids. Understanding the thermal and transport properties of ILs is essential for their potential application in heat exchangers, cooling systems, and other heat transfer processes. ILs are known for their unique properties, and this study aims to quantify and analyze these properties for practical use. In conjunction, the combination of experimental measurements and molecular dynamics simulations is motivated by the desire to gain a comprehensive understanding of the molecular-level behavior of ILs. This approach provides insights into how the structure and interactions of IL molecules contribute to their thermal and transport properties.

The paper enlightens us on a few key factors on the interaction of Ionic Liquids that we were lacking. Firstly, there is a linear relationship between heat capacity and temperature. This is similarly observed with the density of the ionic liquids, as it decreases with an increase in temperature. This signals that ionic liquids could become a vapor at a reasonable temperature. Most importantly, the molar heat capacity of the ionic liquids are nearly twice as large as that of Therminol VP-1, which also extends to their energy storage densities. This paper allows us to see that ionic liquids are excellent heat transfer fluids at higher working temperatures. However, this paper is referenced with caution due to limited ionic liquid selection, assumptions within the molecular dynamic study, and scalability. While the paper observes favorable results for the selection of fluids, there are thousands of ionic liquids to choose from. Not only that, but many of the properties have to scale for a much bigger system that will include a vaporous ionic liquid. However, the paper still advises the most important parameters for ionic liquids and the general trends that will hold for the same temperature range [4].

D. Ionic liquids as heat transfer fluids – An assessment using industrial exchanger geometries

The paper "Ionic Liquids as Heat Transfer Fluids – An Assessment Using Industrial Exchanger Geometries" by Vishwas V. Wadekar investigates the practicality of using ionic liquids as heat transfer fluids in industrial heat exchangers. Focusing on a specific ionic liquid, 1-butyl-3-methylimidazolium bis[(trifluoromethyl)sulfonyl]imide ([bmim][Tf2N]), the study conducts simulation-based assessments of its heat transfer characteristics in two common industrial heat exchanger geometries: plate heat exchangers and shell and tube heat exchangers.

The findings reveal that although the intrinsic heat transfer coefficients of the chosen ionic liquid are not particularly high, reasonable heat transfer performance can be achieved through careful selection of heat exchanger type, configuration, and the potential use of heat transfer enhancement technology. The study emphasizes the importance of the heat exchanger geometry in maximizing the efficiency of ionic liquids as heat transfer fluids. It also highlights the need for further research into the long-term stability of ionic liquids, especially considering their relatively new introduction compared to traditional heat transfer fluids like Dowtherm A, which was used as a comparative fluid in the simulations. The paper concludes that while the inherent thermal properties of ionic liquids may not be superior, their practical applications can be significantly enhanced with appropriate technological adaptations [5].

IV. Methods

The following section outlines the process for identifying ionic liquids and determining their performance. We start with ionic liquid identification and progress to evaluating the heat pipe operational limits based on sintered wick calculations and finally compare these operational limits in the context of water and ammonia at a similar temperature.

A. ILThermo Database

The ILThermo database [6] contains a record of the experimental data for thousands of ionic liquids with capabilities to search by chemical formula, published journal articles which contain experimental data or chemical properties. After determining the most important fluid properties from our literature review, we conduct a search based on the following properties: density, pressure, viscosity, surface tension, thermal conductivity, latent heat of vaporization. Out of the required parameters, ILThermo lets us search for all except latent heat of vaporization, which we need to derive ourselves (describe process). We use a Python data scraper [7] to help us aggregate all the relevant data for one ionic liquid and determine which ones have the most complete data available for our temperature. From our literature review, we also consult property tables from manufacturers, especially for proprietary ionic liquids which are not searchable on ILThermo.

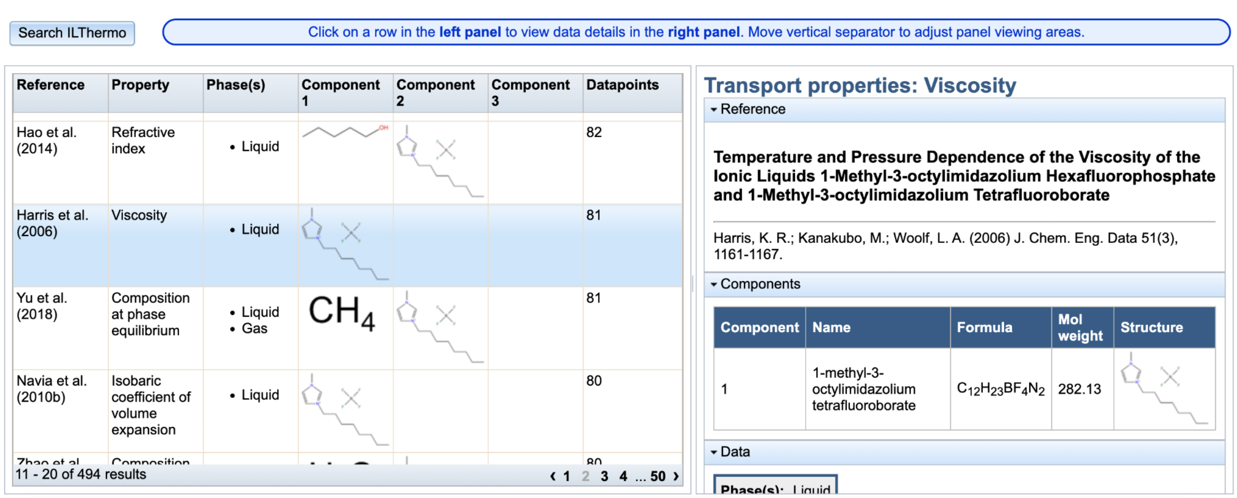

Figure 1: Search interface of ILThermo database showing results for 1-methyl-3-octylimidazolium tetrafluoroborate properties

B. Ionic Liquid Selection Process

After aggregating the data from ILThermo and other sources as part of our literature review, we decide to focus on four ionic liquids in particular: Therminol VP-1, [bmim][Tf2N], [HMIM][BF4], and [P14,6,6,6][NTf2]. The reason for these specific choices is because of the completeness of relevant data at our temperature of interest (350 K), and the fact that they represent one ionic liquid from each of the major groups of ionic liquids as discussed in the second paper in our literature review. Additionally, these ionic liquids include a combination of proprietary (Therminol VP-1) and experimental ionic liquids. The fluid properties for the four ILs are summarized in Table 1.

Table 1: Fluid properties for selected ionic liquids at around 350K

Ionic Liquid	Liquid Density [kg/m3]	Thermal Conductivity [W/m-K]	Viscosity [mPa-s]	Heat of vaporization [kJ/kg]	Surface Tension [N/m] [9]
Therminol VP-1 [8]	1015	0.13	1.28	382.9	36.6
[bmim][Tf2N]	1279	0.1166	2.162	334.46	45.33
[HMIM][BF4]	1095	0.1775	50	622.1	37.33
[P14,6,6,6][NTf2]	1066	0.137	337	236.3	29.55

C. Heat Pipe Operational Limit Calculation using MATLAB

After determining what ionic fluids to use for our parametric study, we check the 5 different heat pipe limits that are contained in [10]. These limits include Capillary, Viscous, Sonic, Entrainment, and Boiling. The capillary limit is the maximum rate at which a working fluid can be wicked, or drawn, by the capillary forces in the porous structure of the heat pipe wick. If the heat input to the heat pipe exceeds this limit, the capillary forces may not be able to transport the working fluid quickly enough, leading to dryout and reduced heat transfer efficiency. The viscous limit is related to the viscous resistance of the working fluid in the heat pipe. It represents the point where the viscous forces opposing fluid flow become significant enough to affect the overall heat transfer capability. Beyond this limit, increasing the heat input may not result in a proportional increase in heat transfer, and the effectiveness of the heat pipe diminishes. The sonic limit is the maximum heat input to a heat pipe before the working fluid vapor velocity reaches the speed of sound. Beyond this limit, additional heat input can cause a choked flow condition where the

vapor velocity remains constant and any further increase in heat input does not increase the vapor flow rate. Entrainment refers to the phenomenon where vapor carries liquid droplets with it as it travels through the heat pipe. The entrainment limit is the point where the vapor velocity becomes high enough to entrain liquid droplets, potentially causing problems such as reduced heat transfer efficiency or damage to the heat pipe. The boiling limit is the maximum heat input at which the working fluid can absorb heat through the process of boiling.
Beyond this limit, the working fluid may experience dryout, where the liquid is depleted, leading to reduced or even halted heat transfer.. A MATLAB script (linked in the Appendix) is created to streamline the calculations by taking in the variables previously specified as a user input. The heat pipe structure variables are constant unless specified otherwise and are hard-coded within the script. This also allows us to change the parameters at a faster rate compared to other options. Once set, the script outputs the numerical values of the 5 different heat pipe limits, in units of Watts. Figure 2 shows the equations functions to calculate these limitations.

Capillary Limitation

$$\Delta P_c = \frac{2\sigma}{r_{eff}} \cdot cos\theta$$

$$Q_c = \frac{\sigma_l \cdot \rho_l \cdot l_v}{\mu_l} \cdot \frac{K \cdot A_w}{l_{eff}} \cdot \left(\frac{2}{r_{eff}} \cdot \frac{\rho_l \cdot g \cdot l_t \cdot cos\psi}{\sigma_l}\right)$$

Viscous Limitation

$$Q_v = \frac{A_v \cdot r_v^2 \cdot l_v \cdot \rho_v \cdot P_v}{16 \cdot \mu_v \cdot l_{eff}} \cdot \left(1 - \frac{P_{v,c}^2}{P_v^2}\right)$$

Sonic Limitation

$$Q_s = 0.474 \cdot A_v \cdot l_v \cdot (\rho_v \cdot P_v)^{0.5}$$

Entrainment Limitation

$$Q_e = A_v \cdot l_v \cdot \left(\frac{\rho_v \cdot \sigma_l}{2 \cdot r_{c,ave}}\right)^{0.5}$$

Boiling Limitation

$$Q_b = \frac{4\pi \cdot l_{eff} \cdot \lambda_{eff} \cdot T_v \cdot \sigma_l}{l_v \cdot \rho_v \cdot ln\frac{r_i}{r_v}} \cdot \left(\frac{1}{r_n} - \frac{1}{r_{eff}}\right)$$

Figure 2: Heat Pipe Limitations obtained from [10]

D. Heat Pipe CAD

The dimensions of the Heat Pipe used in this study are based on the dimensions of the heat pipe utilized in [10] to be able to compare the limits of the ionic liquids we select to the limits of the heat transfer fluid outlined in [10]. Table 2 outlines the dimensions used to create a CAD model of the heat pipe.

Table 2: Dimensions of Sintered Wick Heat Pipe

Inner Container Radius (m)	0.0065
Vapor Core Radius (m)	0.005
Wick Cross-Sectional Area (m^2)	0.000054
Total Length of Heat Pipe (m)	0.5

While [10] utilizes both a sintered and grooved wick structure. We choose to focus on the sintered wick structure rather than the grooved wick structure. There are a few main reasons for this: there is greater discussion of operational limits with a sintered wick structure, and the dimensions of the sintered wick are described in greater detail than that of the grooved wick. Additionally, the advantages of pairing a sintered wick with ionic liquids may be beneficial to their overall heat transfer performance. Sintered wick heat pipes tend to have stronger capillary action, and due to the larger viscosities found in ionic liquid, having a higher pressure force to drive the fluid can decrease the issue of higher viscous liquids. Sintered wick heat pipes are also designed to withstand higher temperatures. The goal of our study is to be able to determine whether ionic liquids allow for TCS performance at higher operating temperatures, not only must the working fluid withstand extreme temperatures but also the structural constraints of the equipment.

V. Results and Discussion

This section outlines our results from our MATLAB script in Table 3 using the ionic liquid fluid properties from Table 1. We also compare our findings with the working fluid used in [10] and with conventional working fluids. We then outline the changes in operational limits after changing the heat pipe diameter and discuss trends in these changes.

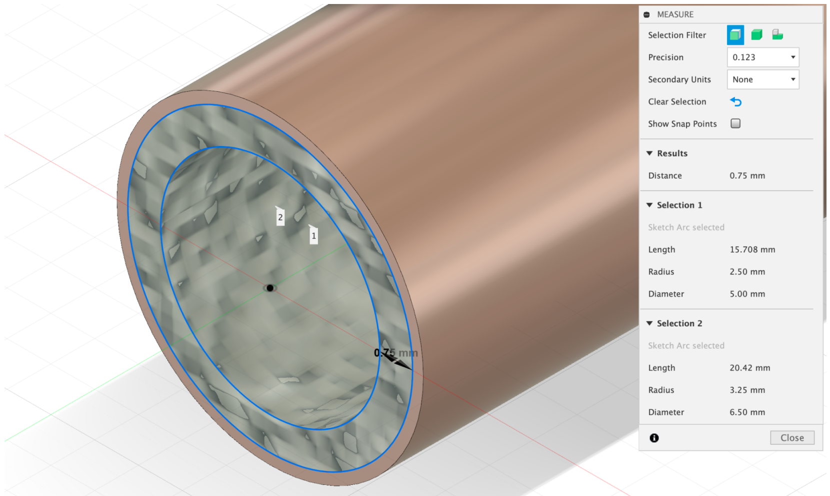

Figure 3: Sintered Wick Heat Pipe CAD Model

Using the CAD model of the heat pipe based on [10], we run each ionic liquid through our MATLAB code in order to get the heat pipe limits. Table 3 below shows the output results.

Table 3: Limits using Original Heat Pipe Design

IL	Capillary	Viscous	Sonic	Entrainment	Boiling
Therminol VP-1	24.52 kW	2.934e-5 W	2.05 kW	23.82 kW	2.76 kW
[bmim][Tf2N]	19.77 kW	2.56e-5 W	1.79 kW	23.1 kW	3.51 kW
[HMIM][BF4]	1.12 kW	4.76e-5 W	3.34 kW	39.08 kW	2.36 kW
$[P_{14,6,6,6}]$[NTf2]	48.77 W	1.81e-5 W	1.27 kW	13.2 kW	3.81 kW

Based on these results, an understanding can be reached behind the significance of every one of these limits. The boiling limit is significantly high with it peaking at 3.81 kW for $[P_{14,6,6,6}]$[NTf2]. The trend of these high boiling limits among the ionic liquids corresponds to their low volatility. It is expected for ionic liquids not to undergo phase changes unless met with far more extreme temperature conditions than what we are examining in this study. Since we are relying on the ionic liquid to be in liquid phase, it is important to take note of the boiling limit, but it does not heavily limit ionic liquid performance for our temperature. We can see that the viscous limit is the most constraining out of all heat pipe operating limits for our chosen ionic liquids. While the other limits are in the magnitude of kW, the viscous limit at its highest value is 4.76e-5 W for [bmim][Tf2N]. It seems reasonable that the viscous limit would be one of the biggest factors to consider in heat pipe performance as ionic liquids tend to be far more viscous than common working fluids. The increased viscosity makes increased flow through a heat pipe more difficult, and more susceptible to low flow conditions. Other limits that seem not to have a significant effect on heat pipe performance for ionic liquids are capillary, entrainment, and sonic limits. The sonic limit primarily affects heat pipes during startup and low-temperature operations. Considering that we are studying ionic liquids under high-temperature conditions, the only significance that the sonic limit has is towards start-up operation. Having a high sonic limit is a great indication for the upper limit of heat transfer performance. The high capillary limit is also a great indication for high capillary pumping power which is necessary given the viscosity of the ionic liquids. In terms of the entrainment limit, given that we are focused on the ionic liquid being in one state throughout its performance, it is expected that it is a high value and should not affect our heat pipe performance.

A. Ionic Liquid Limit Comparison with Conventional Heat Pipe Working Fluids

Table 4: Limits of Heat Pipe with Ammonia and Water as Working fluid [11]

Working fluid	Liquid Density [kg/m^3]	Thermal Conductivity [W/m-K]	Viscosity [mPa-s]	Heat of vaporization [kJ/kg]	Surface Tension [N/m]
Ammonia	505.7	0.3538	0.0803	874.1	0.00977
Water	971.8	0.670	355	2309	0.0678
	Capillary	**Viscous**	**Sonic**	**Entrainment**	**Boiling**
Ammonia	434.2 W	6.6998e-5 W	4.7021 kW	888.46W	0.0875 W
Water	1.641 kW	1.7698e-4 W	12.421 kW	6.1826 kW	4.3446 W

After running our MATLAB script and calculating the limits for a heat pipe using ionic liquid as a working fluid, we compare our results to a heat pipe using conventional working fluids. We gather fluid properties for ammonia and water, input them in the MATLAB script and compile the results in Table 4. Based on the values of the limits for ammonia and water, it is apparent that the limits are lower than those of the ionic liquids. The boiling limit for ammonia and water is significantly lower than the boiling limit for ionic liquids. This speaks to our initial reasoning for looking into ionic liquids. At high temperatures, ionic liquids can remain in a liquid state while conventional working fluids such as ammonia and water begin to reach their critical point and result in ineffective performing heat pipes. Among the various constraints, capillary limitation and viscous limitation emerge as the foremost limiting factors for both ammonia and water. This observation stems from the examination of surface tension and viscosity graphs for ammonia and water across different temperatures. They reveal a pronounced decrease in both surface tension and viscosity with increasing temperature. Notably, surface tension corresponds to capillary limit, enabling liquids to be drawn into and traverse narrow capillaries within a heat pipe, while viscosity is related to viscous limit. Given these characteristics exhibited by ammonia and water, capillary and viscous limitations stand out as the most constraining factors determining the behavior of these liquids.

B. Change in Ionic Liquid Performance Across Varying Heat Pipe Geometries

In our goal to determine the optimal configuration for the new heat pipe, we elect to modify its vapor core radius among other features. Altering the heat pipe's radius, a seemingly simple adjustment proves to be a potent factor owing to its substantial impact on the heat transfer area—a parameter that significantly influences inherent limitations. Following the execution of our MATLAB script and the computation of limits for a heat pipe with varying radii, our findings reveal that achieving a vapor core radius 1.5 times larger than the original radius yields more operating limits. Other than the capillary limitation, other limitations increase up to a factor of 20.

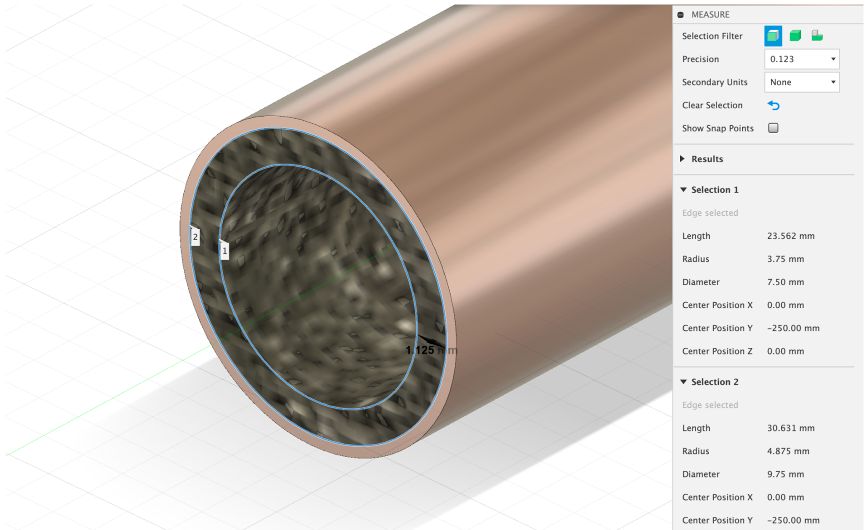

Figure 4: New Sintered Wick Heat Pipe CAD Model with Increased Vapor Core Radius

Table 5: Heat Pipe Limits after increasing vapor core radius

IL	Capillary	Viscous	Sonic	Entrainment	Boiling
Therminol VP-1	24.53 kW	1.49E-4 W	4.63 kW	53.6 kW	23.0 kW
[bmim][Tf2N]	19.80 kW	1.30E-4 W	4.05 kW	52.1 kW	29.3 kW
[HMIM][BF4]	1.12 kW	2.41E-4 W	7.53 kW	87.9 kW	19.7 kW
[$P_{14,6,6,6}$][NTf2]	48.77 kW	9.17E-5 W	2.86 kW	29.7 kW	31.7 kW

VI. Conclusion

In conclusion, this research delves into the promising realm of spacecraft thermal management systems, focusing on the untapped potential of ionic liquids (ILs). While the current models display favorable limitations for heat pipes at temperatures around 350K, surpassing conventional fluids like water and ammonia, this achievement is tempered by significant trade-offs. The absence of exact vaporization temperatures for ILs necessitated reliance on estimates, both for vaporization and vapor density, which might limit the precision of our current understanding. To address this, further research into the specific properties of ILs, such as their heat of vaporization, is essential. Additionally, exploring non-wicked heat pipe designs could be advantageous due to the significant viscous limitations of ILs, potentially keeping them in a more stable liquid phase. Despite these challenges, ILs demonstrate a robust capacity to transport higher heat loads at elevated temperatures, highlighting their potential for future spacecraft missions.

Future work should extend its purview to encompass a comparative analysis with other thermal management technologies, like fluid-pumped loops, to offer a comprehensive understanding of various systems. ILs, often remaining in a liquid state over a broad temperature range, align well with the diverse thermal conditions in space missions. Their low volatility, reduced corrosiveness, and potential for higher heat transport at higher temperatures underscore their suitability for pumped fluid loops. This adaptability, coupled with their reduced risk of fluid loss and less corrosive nature, can enhance system stability and longevity. However, to fully harness the capabilities of ILs, further exploration into their thermal properties and performance in different heat pipe configurations, using tools like Ansys Fluent and physical prototypes, is crucial. Such research will not only refine our models but also pave the way for more effective and reliable thermal management solutions in spacecraft technology.

Appendix

```
function [Q_s,Q_c,Q_v,Q_e,Q_b] = HeatPipeLimit(temp,rho_v,P_v,l_v,Mu_v, Mu_l,
 sigma_l, rho_l, lambda_l, theta, phi)

% The outputs are a measure of each of the heat pipe limits taken from the
% formulas in paper 8
% pick 350K as operating temp
% Some limits are dependent on the temperature we set at the evaporator.
% This is dependent on the heat pipe design and can be changed

% The outputs: Q_s is the sonic limit, Q_c is the capillary limit, Q_v is
% the viscous limit, Q_e is the entrainment limit, Q_b is the boiling limit

% The heat pipe inputs: temp is operating temperature in K (300-500K), rho_v
 is the vapor
% density at the evaporator exit for the given heat pipe design, P_v is the
% vapor pressure at the evaporator exit for the given heat pipe design,
% Mu_v is the viscosity evaporator exit for the given heat pipe design.

% The fluid property inputs: l_v is the latent heat of vaporization, Mu_l is
 the liquid
% viscosity, sigma_l is the surface tension of the liquid, rho_l is the
% liquid density, lamdba_l is the liquid thermal conductivity, theta and
% phi are the contact angle and axial orientation that can be changed by us

% (using paper 8 as a basis for physical pipe properties)
r_i= 0.0065; %inner container radius
r_v=0.005 ; %vapor core radius
l_e= 0.15; % length of evaporator
l_c= 0.15;%length of condensor
l_ad= 0.2; %adiabatic length of heat pipe
l_t= l_e+l_ad+l_c;%total length of the pipe
l_eff=0.5*(l_e+l_c)+l_ad; %effective length of pipe in evaporator
A_v= pi*r_v^2;%cross-sectional area of vapor core
lambda_m=393; %thermal conductivity of material

%Sintered capillary structure Parameters
emm= 0.65; %porosity
h=0.0015; %Width of Capillary Structure
d=0.0001; %Sphere Diameter
K=(d^2*emm^3)/(150*(1-emm)^2); % Permeability
r_eff= 0.21*d; %wick capillary radius in the evaporator
lambda_eff=lambda_l*((2*lambda_l+lambda_m-2*(1-emm)*(lambda_l-lambda_m))/
(2*lambda_l+lambda_m+(1-emm)*(lambda_l-lambda_m))); %effective thermal
 conductivity of wick and working fluid
A_w=pi*(r_i^2-(r_i-h)^2); %wick cross-section
```

```
% Constants
g=9.8;
r_n=r_v;
P_v_c=10000; %Pressure of vapor at condenser.


% Sonic Limit
Q_s=0.474*A_v*l_v*(rho_v*P_v)^0.5;

% Capillary Limit

Delta_P_c=((2*sigma_l)/r_eff)*cosd(theta); % change in capillary pressure are

Q_c= ((sigma_l*rho_l*l_v)/Mu_l)*((K*A_w)/l_eff)*((2/r_eff)-
((rho_l*g*l_t*cosd(phi))/sigma_l));

% Viscous Limit

Q_v=((A_v*r_v^2*l_v*rho_v*P_v)/16*Mu_v*l_eff)*(1-(P_v_c^2)/(P_v^2));

% Entrainment Limit

Q_e= A_v*l_v*((rho_v*sigma_l)/(2*r_eff))^0.5;

% Boiling Limit

Q_b= ((4*pi*l_eff*lambda_eff*temp*sigma_l)/(l_v*rho_v*log(r_i/r_v)))*((1/r_n)-
(1/r_eff));

end
```

MATLAB code to calculate Heat Pipe Operating Limits

Acknowledgments

We would like to acknowledge Professor Sadaf Sobhani for inspiring us with our research topic into Ionic Liquids as well as providing us with useful resources and feedback throughout the project.

References

[1] Minea, A. A., "Overview of Ionic Liquids as Candidates for New Heat Transfer Fluids," International Journal of Thermophysics, Vol. 41, 2020, Article No. 151. doi: 10.1007/s10765-020-02727-3.

[2] Fabre, E. and Murshed, S. M. S., "A Review of the Thermophysical Properties and Potential of Ionic Liquids for Thermal Applications," Journal of Materials Chemistry A, Vol. 2021, No. 29, 2021.

[3] Ghandi, K., "A review of ionic liquids, their limits and applications," *Green and Sustainable Chemistry*, vol. 04, 2014, pp. 44–53.

[4] Liu, H., Maginn, E., Visser, A. E., Bridges, N. J., and Fox, E. B., "Thermal and Transport Properties of Six Ionic Liquids: An Experimental and Molecular Dynamics Study," Ind. Eng. Chem. Res., Vol. 51, No. 21, 2012, pp. 7242–7254. doi: 10.1021/ie300222a.

[5] Wadekar, V. V., "Ionic Liquids as Heat Transfer Fluids – An Assessment Using Industrial Exchanger Geometries," Journal of Applied Thermal Engineering, Vol. 111, 2017, pp. 1581–1587. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2016.04.156.

[6] "ILThermo," National Institute of Standards and Technology, accessed November 20 2023, https://ilthermo.boulder.nist.gov/.

[7] "pyILT2," Frank Roemer, MIT, accessed November 10 2023, http://wgserve.de/pyilt2/usage.html

[8] Eastman Chemical Company, "Therminol VP-1 Heat Transfer Fluid," available at https://www.therminol.com/sites/therminol/files/documents/TF09A_Therminol_VP1.pdf, Accessed November 15, 2023.

[9] Kilaru, P., Baker, G. A., and Scovazzo, P., "Density and Surface Tension Measurements of Imidazolium-, Quaternary

Phosphonium-, and Ammonium-Based Room-Temperature Ionic Liquids: Data and Correlations," Journal of Chemical Engineering Data, Vol. 52, No. 6, 2007, pp. 2306–2314. doi: 10.1021/je7003098.

[10] Nemec, P., Caja, A., and Malcho, M., "Mathematical Model for Heat Transfer Limitations of Heat Pipe," Mathematical and Computer Modelling, Vol. 57, 2013, pp. 126-136. doi: 10.1016/j.mcm.2011.06.047

[11] GSFC, "Ammonia-Charged Aluminum Heat Pipes with Extruded Wicks," *NASA* Available: https://llis.nasa.gov/lesson/698.

[12] He, G.-D., Fang, X.-M., Xu, T., Zhang, Z.-G., and Gao, X.-N., "Forced Convective Heat Transfer and Flow Characteristics of Ionic Liquid as a New Heat Transfer Fluid Inside Smooth and Microfin Tubes," International Journal of Heat and Mass Transfer, Vol. 91, Dec. 2015, pp. 170–177. DOI: 10.1016/j.ijheatmasstransfer.2015.07.094.

[13] MathWorks, "MATLAB, version R2022b," The MathWorks, Inc., Natick, MA, 2022.