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Pool Boiling Performance of Novec™ 649 Engineered Fluid

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ABSTRACT

A new fluorinated ketone, $C_2F_5C(O)CF(CF_3)_2$, is currently being considered as an environmentally friendly alternative for power electronics cooling applications due to its high dielectric strength and low global warming potential (GWP). Sold commercially by the 3M Company as Novec™ 649 Engineered Fluid, $C_2F_5C(O)CF(CF_3)_2$ exhibits very low acute toxicity while maintaining long-term stability. To assess the general two-phase heat transfer performance of Novec™ 649, pool boiling tests were conducted by resistively heating a 0.01 in. diameter nickel wire at the fluid's atmospheric saturation temperature of 49º C. The nucleate boiling heat transfer coefficient and critical heat flux (CHF) obtained for the fluorinated ketone compare favorably with results obtained for FC-72, a fluorocarbon widely used for the direct cooling of electronic devices. Initial results indicate that Novec™ 649 may prove to be a viable alternative to FC-72 and other haloalkanes for the cooling of high power density electronic devices.

Keywords: Pool boiling, Fluorinated ketone, Novec™ 649, Low GWP fluids, Power electronics cooling

INTRODUCTION

The cooling of microelectronics, power electronics, and other high power density devices poses a continuing challenge for thermal engineers. Considering that the performance of electronic devices degrades rapidly with increasing temperature, it is crucial that proper thermal management techniques are integrated into the design of electronic systems. Air cooling is often insufficient to maintain proper operational temperatures in devices such as insulated-gate bipolar junction transistors (IGBT's), even when coupled with large heat sinks and forced convection setups. Indirect cooling using water offers higher cooling capacities than air cooling alone, but still requires large heat exchangers and creates corrosion issues which could lead to failure of the electronic device. Direct immersion cooling of electronic devices has been a popular alternative to air and indirect water cooling due to the much higher heat transfer coefficient without the need for large heat sinks attached to the electronic device.

Bergles [1], Chu [2], and others have long recognized the difficulties associated with the cooling of electronic devices. The use of dielectric fluids to cool electronics, both directly and indirectly, has been researched since the late 1960's [2]. Two-phase direct immersion cooling offers high heat transfer coefficients coupled with the size reduction of secondary heat exchangers or heat sinks. However, finding a fluid with good dielectric properties, good thermophysical properties, low toxicity, low flammability, low environmental impact, long-term stability, and acceptable chemical compatibility with electronic materials has often led to significant compromises in reducing environmental impact or in fluid performance.

Many chlorofluorocarbons (CFC's) and hydrochlorofluorocarbons (HCFC's) are suitable for power electronics cooling applications, but have a significant environmental impact, as they are ozone-depleting. The 1987 Montreal Protocol enacted legislation essentially banning all CFC's and requiring the phasing out of HCFC's [3]. Hydrofluorocarbons (HFC's) have replaced CFC's and HCFC's for nearly all refrigeration and air conditioning applications. One such HFC, 1,1,1,2-tetrafluoroethane (R-134a), is now widely used in automotive air conditioning systems, and has been used for the indirect cooling of electronic devices. Recent work at the National Transportation Research Center has also shown the potential for direct immersion cooling of power electronics for hybrid-electric vehicles using R-134a [4].

Perfluorocarbons (PFC's) have been widely used for the cooling of power electronics for over four decades. They offer high dielectric strengths, low toxicity and adequate heat transfer properties. Perfluorocarbons are currently used as heat transfer fluids for supercomputers, avionics, and many mission-critical military electronics. Perfluorohexane (C_6F_{14}), one such fluorocarbon, is available commercially as FC-72. Perfluorocarbons, along with HFC's, are non-ozone depleting, and are therefore excluded from the Montreal Protocol. However, perfluorocarbons and hydrofluorocarbons are both greenhouse gases, and on a per mass basis, contribute significantly to global warming.

Greenhouse gases have a net positive effect on radiative forcing. Radiative forcing is typically defined as the change in irradiance at the tropopause, the atmospheric boundary between the troposphere and the stratosphere [5]. Radiative forcing is the cause of the well-known greenhouse effect. The infrared absorption and emission characteristics of a gas partially determine its significance as a greenhouse gas, along with other factors such as the atmospheric lifetime. The global warming potential (GWP) is a means of expressing the cumulative

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contribution of a unit mass of gas to radiative forcing over a designated time period relative to some reference gas [6]. Carbon dioxide is almost always used as the reference gas, with a GWP of 1. The global warming potential accounts for the net of direct and indirect contributions to global warming from a gas. The atmospheric lifetime of a gas primarily depends on the rate at which the gas decomposes from photolyzation or oxidation in the troposphere or stratosphere [7]. Whereas most naturally occurring substances have atmospheric lifetimes of several years, inert HFC's and perfluorocarbons can have atmospheric lifetimes on the order of thousands of years. The 1997 Kyoto Protocol set forth by the United Nations seeks to reduce greenhouse gas emissions worldwide. The Kyoto Protocol includes hydrofluorocarbons and perfluorocarbons, calling for reductions in their production and use [8].

With the potential reduction in the future availability of HFC's and perfluorocarbons, there has been considerable interest in low global warming potential coolants to replace perfluorocarbons and other more environmentally disruptive haloalkanes for the cooling of power electronics and other devices. Hydrofluoroethers (HFE's) are one potential alternative, offering good dielectric properties with low global warming potentials. Another alternative is a new fluorinated ketone, $C_2F_5C(O)CF(CF_3)_2$, sold commercially by the 3M Company as Novec^{TM} 649 Engineered Fluid. $C_2F_5C(O)CF(CF_3)_2$ is particularly attractive due to its high dielectric strength, similar thermophysical properties to those of perfluorohexane, and global warming potential of 1 over a 100 year timeframe [9]. Table 1 lists relevant properties of $C_2F_5C(O)CF(CF_3)_2$ and perfluorohexane [9].

This work investigates the two-phase heat transfer performance of Novec^{TM} 649 Engineered Fluid by boiling the saturated fluid at atmospheric pressure from a 0.01" nickel wire. As a basis for comparison, saturated FC-72 is also boiled at atmospheric pressure using the same boiling apparatus. Results are also compared to those expected by theory. Additionally, prospective enhancement techniques for improving the boiling heat transfer properties of $C_2F_5C(O)CF(CF_3)_2$ are discussed.

EXPERIMENTAL

Property Measurements of Novec^{TM} 649

Various properties of $C_2F_5C(O)CF(CF_3)_2$ were measured at room temperature, including liquid kinematic viscosity, surface tension, liquid density, and liquid thermal conductivity. Results are summarized in Table 2. Property measurement values agreed well with values reported by 3M, except for the value of the thermal conductivity. Although the KD2 Pro Thermal Properties Analyzer is purportedly capable of measuring fluids with thermal conductivities as low as 0.02 W/m-K using the KS-1 probe, there may have been convection effects, introducing additional error to the measurement.

Attempts were made to measure the contact angle of Novec^{TM} 649 on smooth aluminum and stainless steel surfaces. However, the fluorinated ketone was almost perfectly wetting due to the low surface tension of the liquid. Figure 1 shows measured contact angles for $C_2F_5C(O)CF(CF_3)_2$ on aluminum and stainless steel surfaces 100ms after droplet contact.

Table 1: Relevant Properties of Novec^{TM} 649 and FC-72 at 25 ºC. (Adapted from Ref. [9])

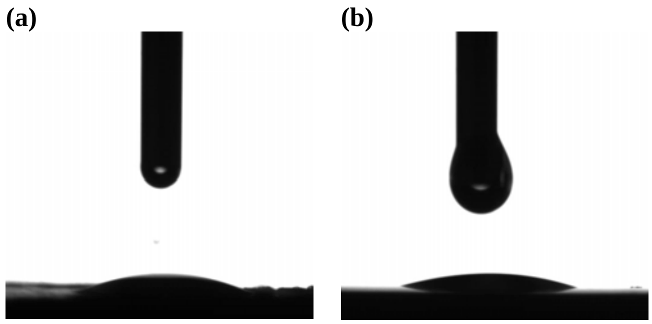
Molecular Formula	$C_2F_5C(O)CF(CF_3)_2$	C_6F_{14}
Fluid Type	Fluoroketone	Perfluorocarbon
Trade Name (3M^{TM})	Novec^{TM} 649 Engineered Fluid	Fluorinert^{TM} Electronic Liquid FC-72
Normal Boiling Point (ºC)	49	56
Freezing Point (ºC)	<-100	<-100
Critical Temperature (ºC)	169	178
Critical Pressure (MPa)	1.87	1.83
Closed Cup Flashpoint (ºC)	None	None
Open Cup Flashpoint (ºC)	None	None
Surface Tension (mN/m)	11.4	12.0
Thermal Conductivity (W/m-K)	0.059	0.057
Liquid Specific Heat (J/kg-K)	1103	1050
Liquid Density (kg/m^3)	1610	1680
Kinematic Viscosity (cSt)	0.42	0.40
Latent Heat (kJ/kg)	88	88
Vapor Pressure at 25 ºC (kPa)	40.4	30.9
Vapor Pressure at 100 ºC (kPa)	441	350
Resistivity (Gohm-cm)	10,000	1,000,000
Dielectric Constant	1.84	1.76
Dielectric Strength (kV at 2.54 mm)	~40	~40
Solubility of H_2O in fluid (ppmw)	21	10
Atmospheric Lifetime (years)	0.014	3200
Global Warming Potential (100 year Integration Time Horizon)	1	9300
Ozone Depletion Potential	0	0

Table 2: Measured Properties of Liquid Novec^{TM} 649.

Property	Apparatus	Value
Liquid Density (at 21º C)	Volumetric Flask and Precision Balance	1607±2 kg/m^3
Liquid Kinematic Viscosity (at 21ºC)	Capillary Viscometer	0.4243±0.0048 cSt
Surface Tension (at 23º C)	Sigma 703 Tensiometer	11.47±0.23 mN/m
Liquid Thermal Conductivity (at 23º C)	KD2 Pro Thermal Property Analyzer	0.092±0.01 W/m-K

Pool Boiling Experiments

The boiling heat transfer coefficient and critical heat flux were measured for clean nickel wires boiled in pure $C_2F_5C(O)CF(CF_3)_2$ and pure FC-72 using the pool boiling apparatus depicted in Figure 2. All boiling experiments were conducted at atmospheric pressure. For the boiling experiments, the wire was heated resistively using a Sorensen



θ=12° θ=18°

Figure 1: Contact Angle 100 ms After Droplet Contact for (a) smooth stainless steel and (b) smooth aluminum.

SRL DC power supply. While the temperature controlled hot plate brought the test fluid up to saturation temperature, the wire surface was degassed by operating at low heat fluxes. An Agilent Technologies 34980A Data Acquisition System measured the voltage drop across the wire, along with the voltage drop across a shunt resistor to determine the current passing through the wire. The heat flux through the wire was calculated by:

$$q'' = \frac{IV}{\pi DL} \tag{1}$$

A type K thermocouple measured the temperature of the test bath to ensure it remained at saturation. The temperature of the nickel wire was calculated using the temperature coefficient of resistance method, where the change in electrical resistance of the wire was correlated to the temperature change of the wire using:

$$R(T) = R(T_0)[1 + \alpha \Delta T] \tag{2}$$

Nickel was chosen due to its high sensitivity in electrical resistivity over the temperature range of interest (i.e. large temperature coefficient of resistance), as is the case for most pure metals when compared to metal alloys. The linearized temperature coefficient of resistance, α, for the nickel wire was measured as 0.0056 K^{-1} from 25 ºC to 75 ºC. A Biot-type analysis reveals that one may approximate the surface temperature of the wire as equal to the average radial temperature due to the wire's small diameter.

Boiling tests were conducted by increasing the power in steps until CHF was reached. At CHF, the nickel wire typically became red hot but did not fail. The heat flux and wall superheat were determined at each power step for the purpose of plotting boiling curves and calculating the effective heat transfer coefficient. The effective heat transfer coefficient is given by Newton's Law of Cooling:

$$q'' = h_{eff}(T_w - T_{sat}) \tag{3}$$

Measurement uncertainty was typically 3.7% or less for the heat flux, 12% or less for the wall superheat, and 13% or less for the heat transfer coefficient. Uncertainty in the wall superheat and heat transfer coefficient was primarily due to the uncertainty associated with the linearized temperature coefficient of resistance for the nickel wire.

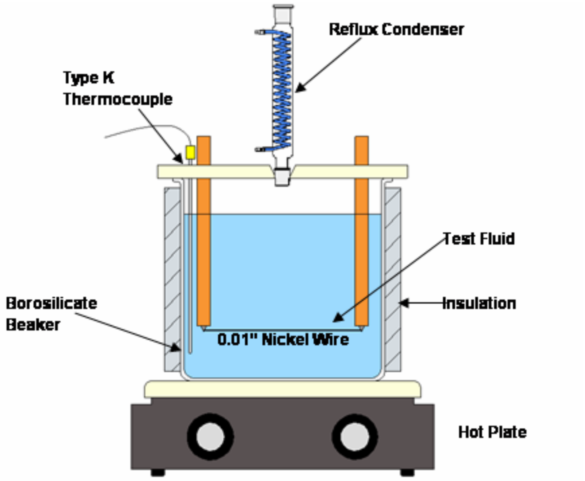


Figure 2: Schematic of the Wire Boiling Setup.

RESULTS

Figure 3 shows boiling curves for 0.01" nickel wire in Novec^{TM} 649 and perfluorohexane. For clarity, only the natural convection and nucleate boiling regimes are plotted. Table 3 lists the average critical heat flux values measured for each fluid over three nominally identical tests. For comparison, Kim, Rainey, et al. obtained a CHF of 170 kW/m^2 at a superheat of ~30 ºC for the pool boiling of saturated FC-72 from a 390 µm (0.15") platinum wire at atmospheric pressure [10]. Liu et al. obtained a CHF of 232 kW/m^2 at a superheat of ~15 ºC for the pool boiling of saturated FC-72 from a flat surface at atmospheric pressure [11]. However, these comparisons are cursory, as boiling geometry and surface material strongly influence CHF and the wall superheat.

In Figure 3, note the clear distinction between the natural convection regime and the nucleate boiling regime for both fluids. Figure 4 illustrates the sudden change at the onset of nucleate boiling for Novec^{TM} 649, with nucleation sites activating suddenly across the wire, resulting in a large temperature drop. Similar behavior was observed for the onset of nucleate boiling in saturated FC-72. Figure 5 shows boiling from the wire in Novec^{TM} 649 immediately following the departure from nucleate boiling, at which point the wire resistance spiked, resulting in a large power increase. Figure 6 shows an interesting steady-state phenomenon, where after reducing the heat flux in the film-boiling regime, the ends of the wire quenched, returning to nucleate boiling, while the middle section continued to experience film boiling.

Table 3: Average Critical Heat Flux Values Measured for FC-72 and Novec^{TM} 649. Also listed are predicted CHF values calculated from the Zuber correlation for small cylinders.

Test Fluid	**Average CHF (kW/m^2)**	**Std. Dev.†**	**Predicted CHF (kW/m^2)**
FC-72	220	8.31%	~224
Novec^{TM} 649	200	0.52%	~208

† Percent of average CHF, for three nominally identical tests.

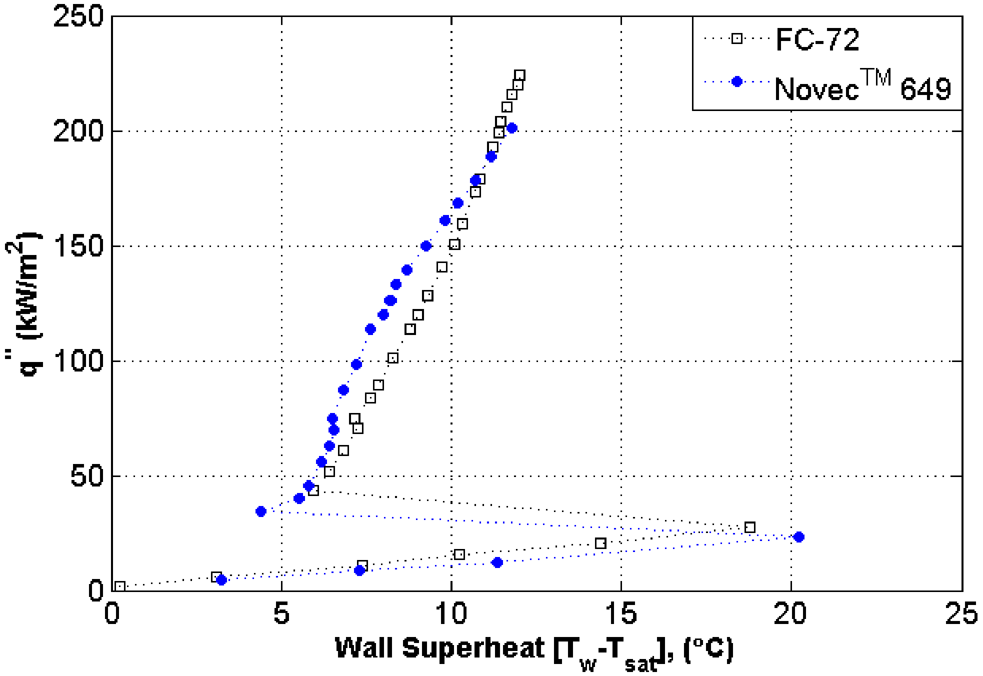


Figure 3: Typical Pool Boiling Curves Obtained for a 0.01" Nickel Wire Immersed in Saturated FC-72 (squares) and Saturated Novec^{TM} 649 (circles) at atmospheric pressure. Recall that the saturation temperature of Novec^{TM} 649 is approximately 7 °C lower than that for FC-72, so the absolute surface temperature will be lower.

Figure 7 shows the effective heat transfer coefficient plotted against the heat flux. The heat transfer coefficient for $C_2F_5C(O)CF(CF_3)_2$ closely matches that of the perfluorocarbon FC-72. However, one must also consider that the saturation temperature of $C_2F_5C(O)CF(CF_3)_2$ is 7 ºC lower than that of perfluorohexane. Therefore, if used for two-phase cooling of electronic devices, one might expect the Novec^{TM} 649 fluid to keep the device surface significantly cooler than FC-72.

DISCUSSION

Boiling Properties

The incipience of boiling for both Novec^{TM} 649 and FC-72 occurs after a large temperature increase in the natural convection region, followed by a considerable drop upon activation of nucleation sites. This onset of nucleate boiling temperature overshoot is contrary to the classic wall superheat requirement calculated using the Young-Laplace and Clausius-Clapeyron equations,

$$T_w - T_{sat} = \frac{2\sigma T_{sat} v_{fg}}{h_{fg} r_c} \qquad (4)$$

if r_c is taken to be the radius of a typical micro-cavity on the surface. For low surface tension liquids, one would expect the superheat for activation to be lower than for high surface tension liquids such as water based on equation (4). Carey explains the importance of the radius of the vapor nucleus for the incipience of boiling, and that the radius of the vapor nucleus is not necessarily equivalent to the cavity radius, but

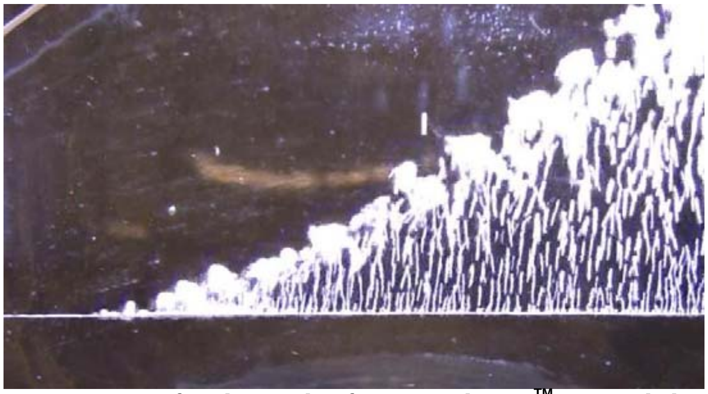


Figure 4: Onset of Nucleate Boiling for Saturated Novec^{TM} 649. With the heat flux constant, nucleation sites activated rapidly across the wire.

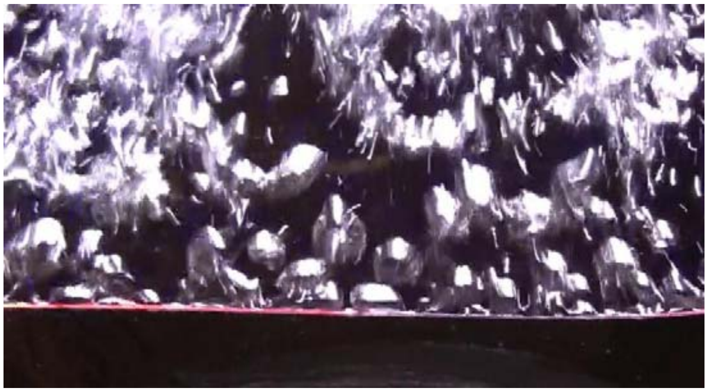


Figure 5: The Nickel Wire Immediately Following the Critical Heat Flux for Novec^{TM} 649. The wire resistance increased drastically, leading to a rapid power excursion. The wire deformed as a result of the high temperature.

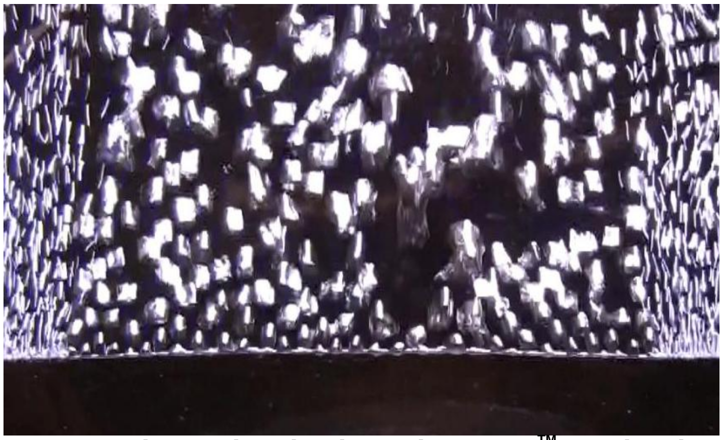


Figure 6: Steady-state Film and Nucleate Boiling in Novec$^{\text{TM}}$ 649. The ends of the wire have quenched, whereas the center remains in the film boiling regime.

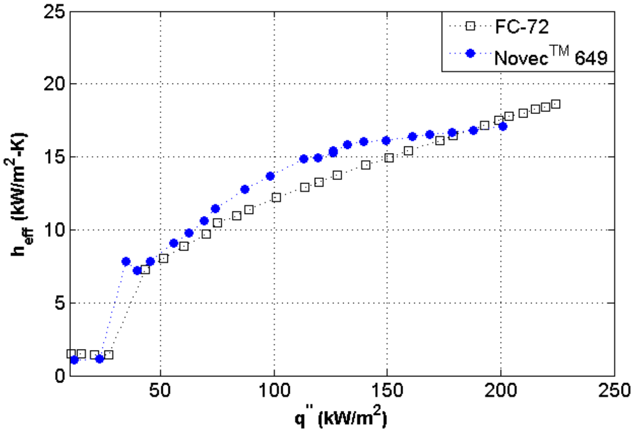


Figure 7: Effective Heat Transfer Coefficient versus Heat Flux for FC-72 and Novec$^{\text{TM}}$ 649.

rather strongly dependent on the contact angle [12]. For low contact angle (well-wetting) fluids, one may not assume that the radius of the vapor nucleus equals that of the cavity. The fluorinated ketone and perfluorocarbon investigated in this study are very well-wetting, resulting in partial or complete flooding of cavities. Anderson and Mudawar discuss this phenomenon for perfluorocarbons, noting that small heaters are even more susceptible to large incipience excursions. They explain that rapid activation patterns are more significant on small heaters since the surface area fraction of the heater affected by a single nucleation site is larger [13]. Marto and Lepere [14], among others, have observed similar trends for boiling incipience in fluorocarbons. Bar-Cohen addresses the superheat excursion phenomenon in detail, also pointing out that enhanced surfaces typically do not alleviate the effect [15]. The temperature overshoot is cause for concern in two-phase electronics cooling systems, as it may result in device temperatures significantly exceeding steady-state operational temperatures.

Although not shown in Figure 3, a hysteresis in the boiling curve was observed for both Novec$^{\text{TM}}$ 649 and FC-72 when the heat flux was reduced after operating in the nucleate boiling regime. As the heat flux was reduced below the level at which boiling incipience occurred, nucleation sites deactivated gradually, skipping the temperature overshoot seen initially. This is likely due to the entrapment of vapor in the nucleating cavities, leading to lower wall superheat requirements to maintain nucleation.

Even with the hydrodynamic instability theory falling under criticism in recent years for its failure to account for surface properties such as wettability [16], the simplified Kutateladze-Zuber correlation [17, 18], shown in equation (5), is still useful for predicting the critical heat flux due to its applicability to a wide range of fluids.

$$q''_{CHF} = K\rho_g h_{fg}\left[\frac{g\sigma(\rho_f-\rho_g)}{\rho_g^2}\right]^{1/4} \qquad (5)$$

Treating the wire as a small horizontal cylinder and using the Kutateladze-Zuber correlation with the appropriate correction factor for finite bodies [19], one may calculate the expected CHF of Novec$^{\text{TM}}$ 649 and FC-72. Using saturated properties for both fluids, one calculates the predicted CHF as ~208 kW/m^2 for Novec$^{\text{TM}}$ 649 and as ~224 kW/m for FC-72 boiling at atmospheric pressure from a 0.01" diameter horizontal wire. The experimentally determined average CHF values are remarkably close to those predicted by the theory.

Techniques for Enhancing Boiling Heat Transfer of Novec$^{\text{TM}}$ 649 Engineered Fluid

Though Novec$^{\text{TM}}$ 649 Engineered Fluid displays heat transfer performance comparable to that of FC-72, lower operating temperatures and increased heat dissipation are required to maximize the performance of new compact power electronics and other devices. As such, there is considerable interest in developing effective means of enhancing the nucleate boiling heat transfer coefficient for such fluids. Surface modification is a proven technique for enhancing the nucleate boiling heat transfer coefficient. Two general approaches to surface modification exist for increasing the nucleate boiling heat transfer coefficient. The first involves increasing the number of cavities for nucleation on a surface by altering the surface structure. This may be achieved through surface roughening, other mechanical treatments such as lapping, or the deposition of porous coatings. A larger nucleation site density typically increases the net rate of vapor production, thereby removing more heat from a surface and keeping it cooler. Berenson demonstrated variations in the heat transfer coefficient of up to 600% by altering surface roughness [20]. Webb summarizes a number of surface treatments from 1931 onward, including abrasion treatments, electroplating, lapping, and porous coatings [21]. Webb indicates that many abrasion treatments offer only temporary increases to the boiling heat transfer coefficient, whereas other treatments, such as porous coatings, offer long-term enhancement of the boiling heat transfer coefficient and can also enhance the critical heat flux.

The other approach to enhancing heat transfer is to alter the chemical constituency of a surface, thereby altering the wetting properties which in turn affects the wall superheat required to activate a given cavity. For example, Young and Hummel demonstrated that adding polytetrafluoroethylene (PTFE) spots to a heater substantially increased the boiling heat transfer coefficient [22]. The enhancement can be attributed to the reduced wettability of water on the PTFE, resulting in more vapor entrapment and preferential nucleation from those sites Furthermore, combinations of treatments to alter both surface structure and chemical constituency offer optimum enhancement of the nucleate boiling heat transfer coefficient. Young and Hummel demonstrated that a pitted surface with PTFE inclusions outperformed surfaces that had been either pitted or treated with PTFE, but not both [22].

Considering that Novec™ 649 has low surface tension and is well-wetting for most surfaces, it may be difficult to develop a surface that would substantially increase the contact angle of Novec™ 649. To maximize vapor entrapment in cavities and thereby lower the superheat required for nucleation, an ideal surface treatment would decrease the wettability of Novec™ 649 around micro-cavities on the surface.

Alteration of surface structure, on the other hand, offers a promising means of enhancing the boiling heat transfer coefficient of low surface tension, well-wetting fluorinated liquids, including Novec™ 649. Kim, Rainey, et al. have demonstrated that a microporous diamond coating significantly enhances the pool boiling heat transfer coefficient and the critical heat flux for FC-72, attributing the increase in the nucleate boiling heat transfer coefficient to a higher nucleation site density imparted by the microporous coating [10]. Tuma has demonstrated enhancement in both the heat transfer coefficient and critical heat flux through the use of metallic microparticle coatings for both hydrofluoroethers [23] and Novec™ 649 [9].

CONCLUSION

This work has investigated the pool boiling performance of a fluorinated ketone, Novec™ 649, and demonstrated that its pool boiling heat transfer properties are comparable to those of the commonly used perfluorocarbon FC-72. Considering the increasing worldwide concern over global warming, and the likelihood of reduction of HFC's and PFC's through the Kyoto protocol, Novec™ 649 may prove to be an attractive alternative to the haloalkanes currently used in the cooling of micro-electronics and power electronic devices. The high power densities associated with such devices continue to pose challenges for thermal management, especially as devices grow more compact in order to fit in hybrid-electric vehicles and other space-constrained applications. Therefore, future work will investigate surface modification as a means of enhancing the two-phase heat transfer capabilities of the fluorinated ketone.

ACKNOWLEDGEMENTS

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NOMENCLATURE

D	wire diameter, m
g	gravitational acceleration, m/s^2
h_{eff}	effective heat transfer coefficient, $W/(m^2\ K)$
h_{fg}	heat of vaporization, J/kg
I	current, A
K	Zuber constant
L	wire length, m
q''	heat flux, W/m^2
q''_{CHF}	critical heat flux, W/m^2
R	electrical resistance, Ω
r_c	cavity radius, m
T	temperature, ºC
T_0	nominal temperature, ºC
T_{sat}	saturation temperature, ºC
T_w	wall temperature, ºC
ΔT	temperature difference, ºC
α	temperature coefficient of resistance, K^{-1}
θ	contact angle, degrees
v_{fg}	specific volume of vaporization, m^3/kg
ρ_f	liquid density, kg/m^3
ρ_g	vapor density, kg/m^3
σ	surface tension, N/m

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