Title: A Combined Active and Passive G-Insensitive Enhanced Micro-nucleation Rate Flow- and Pool boiling Approach

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The technology breakthrough, as reported in [1], needs R&D support to make it g-insensitive and of value to NASA and other Fed Agencies – over and above terrestrial applications (such as making next-generation data centers more efficient with significant waste heat recovery). However preliminary proof of the g-insensitive nature of this approach will likely be available in a year or so, and the reasons for this are described in this topical white paper.

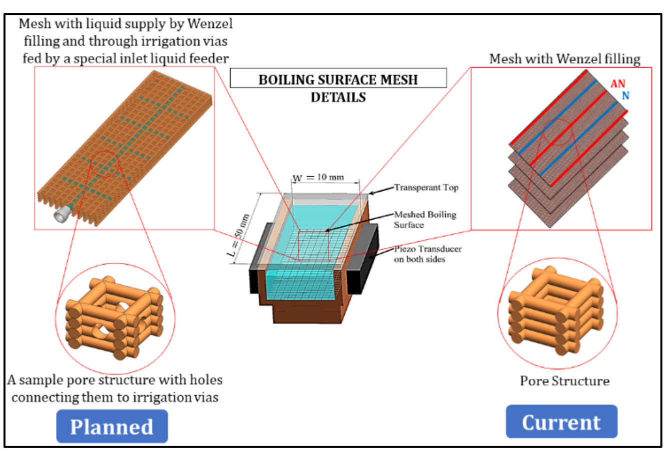
The proposed and twice-tested [1-2] enhanced nucleation flow-boiling approach leads to controlled but explosive growth in micro-scale nucleation rates during flow- or pool-boiling of HFE-7000/7100 (electronics and environment-friendly liquids from 3M, Inc) is described here. There are new ongoing follow-up experimental results [3] in support of the earlier ones [1-2]. Experiments use meshed copper as boiling surface/region and minuscule low-energy mesh-tip vibrations coming from a pair of very thin Piezoelectric-transducers (termed *Piezos*) that are placed and actuated outside the mini-channel heat-sink. The flow-loop control further ensures that the millimeter-scale rectangular cross-section flow-channel (length = 5 cm, width = 1 cm, height = 5 mm), with its bottom heated-surface microstructured by a square-mesh (of height = 0.45 mm, hole area = 0.0193 mm^2 of a single pore cross-section of 0.064 mm^2) operates in a way (Figs. 1-2) – for the flow-control in place – that there are no vapor-compressibility induced flow instabilities [4-8] at system-level (Fig. 2). Further, the flow-control (which can be automated) maintains an all-liquid flow at the inlet, a plug-slug flow-regime by the exit, microstructured boiling-surface/region at the bottom, and separated vapor and liquid flows (with 0.4-0.6 range exit quality) out of the flow-channel (see Fig. 1b). **It is important to note that the flow-control allows for the phase-separation process indicated in Fig. 1b and Fig. 2 can continue to be feasible in 0g/μg.**

The electrical energy consumed for generating micro-vibrations is minuscule by design (within100 mW to 2 W for a large range of cases). Consider a representative experimental run where 150 W is being added to a 5 cm x 1 cm boiling surface (bottom of the meshed region) which is experiencing a driving temperature difference of 25°C above the saturation temperature. For a representative and efficient actuation of Piezos, new steady boiling conditions were reached that led to a 4.8 fold increase in *heat transfer coefficient* (HTC) value – going from about 14000 W/m^2-°C to 67000 W/m^2-°C. At fixed heat-flux of 30 W/cm^2, this follows from the observed rise in test-section pressure and an associated drop in driving temperature difference from 25°C to about 5.2°C. If the temperature difference was instead allowed to regain its 25°C value and critical heat flux (CHF) was suitably increased (say by introducing pumped liquid in the vias of the mesh-pores, see top left corner pic in Fig. 4a) – this would amount to a heat removal rate increase from 150 W to about 720 W.

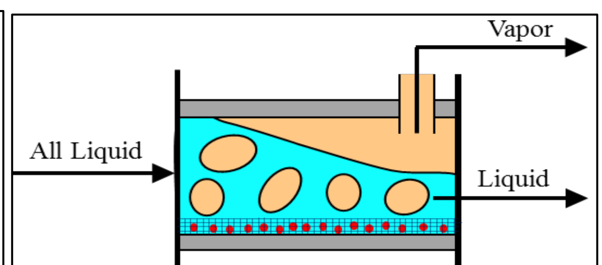
The very *thin* Piezos used here are actuated near resonance, by the Piezos' driver/controller circuit, at a driving sinusoidal voltage frequency f_P (in the 1-2 MHz range) which is very close to one of the *natural* electro-mechanical frequencies of the Piezos – as determined by a suitable *impedance meter*. The Piezos are not electrically driven by a pure sinusoid of frequency f_P, but for good mechanical energy transmission to the mesh-region, they are driven by an *amplitude-modulated* sinusoid – which is achieved by multiplying the driving high-frequency (near f_P) sinusoid by a tunable sinusoidal modulation frequency f_M that are much smaller (in 10 Hz to 2 kHz range) than f_P. The energy-efficient micronucetion rates within the mesh-pores and their ejection from the mesh-tips at very high frequencies likely induce a periodic and slower (near frequency f_M) process consisting of the evacuation of gas bubbles from the mesh-pores and concurrent liquid refilling – by *Wenzel-filling of hydrophilic mesh-pores* with or without other assistance from other pore irrigation mechanisms. These flow-physics hypotheses are amenable to further experimental characterizations by use of laser vibrometers and high-frequency optical imaging – which will likely yield better estimates on bubble sizes and ejection frequencies.

The reason this approach is promising for zero-/micro-gravity and other multi-g environments (such as space, satellites, fighter planes, etc.) is that the low energy consumption for active enhancement is enabled here by one approximate resonance phenomena in the Piezos' material, and several other energy-efficient phenomena associated with micro-bubbles coming up to the mesh-tip holes – where they experience *easy-to-dislodge* and *strong sideways kicking forces* on the vapor bubbles (see Fig. 3, where the low energy mesh-top micro-vibrations are aided by **node-antinode patterns** – as indicated on the top right corner of Fig. 1a)) with an upward pressure-force component (resulting from nucleating micro-bubbles incorporating more and more of phase-change associated new vapor molecules needing to go into small and finite liquid-volume spaces with saturation temperature constraints). **The resulting forces on the high-frequency (f_P) bubbles being ejected off mesh-tops are likely strong enough to overpower ordinary surface and gravity forces that influence nucleating bubbles' formation, growth, and departure mechanisms [9-11] associated with nucleation in passive flow-boiling and pool-boiling setups on the ground [9-11] and in space [12].** Fortunately, before testing the g-independent nature of the flow-physics associated with this new flow-boiling technology [1] on ISS, preliminary verification of the claims are possible and planned for our pool-boiling set up of ours (see Fig. 4). By recording the significant pressure-rise and associated HTC-enhancement phenomena, when one or both Piezos are switched on ([1-2]) on the ground, and showing the phenomena's persistence in multi-g environments associated with the heater in Fig. 4 placed on top of a vibration-table (available at Mich-Tech through one of the Co-PIs) will make a credible case for g-independent nature of the phenomena [1-2] and further verification of this new science and technology on ISS.

Advancing this science and technology on ISS requires relatively small changes in the existing flow-boiling rig designed/used on ISS [12]. The recommended changes for the existing setup have been studied and can be described at a later stage.



(a)



(b)

Fig. 1: ***(a)*** *A representation of Piezos and a mini-channel with a sample depiction of current and planned natures of 3-D micro-structuring of the boiling surface. The red/blue banding of the current mesh-top represents anti-nodes (AN) and nodes (N) associated with excitation-generated standing waves.* ***(b)*** *A nucleate/bubbly regime of operations is ensured by the implemented (for PoC) process control approach for the system in Fig. 2. Piezos' actuated meshed boiling-surface*

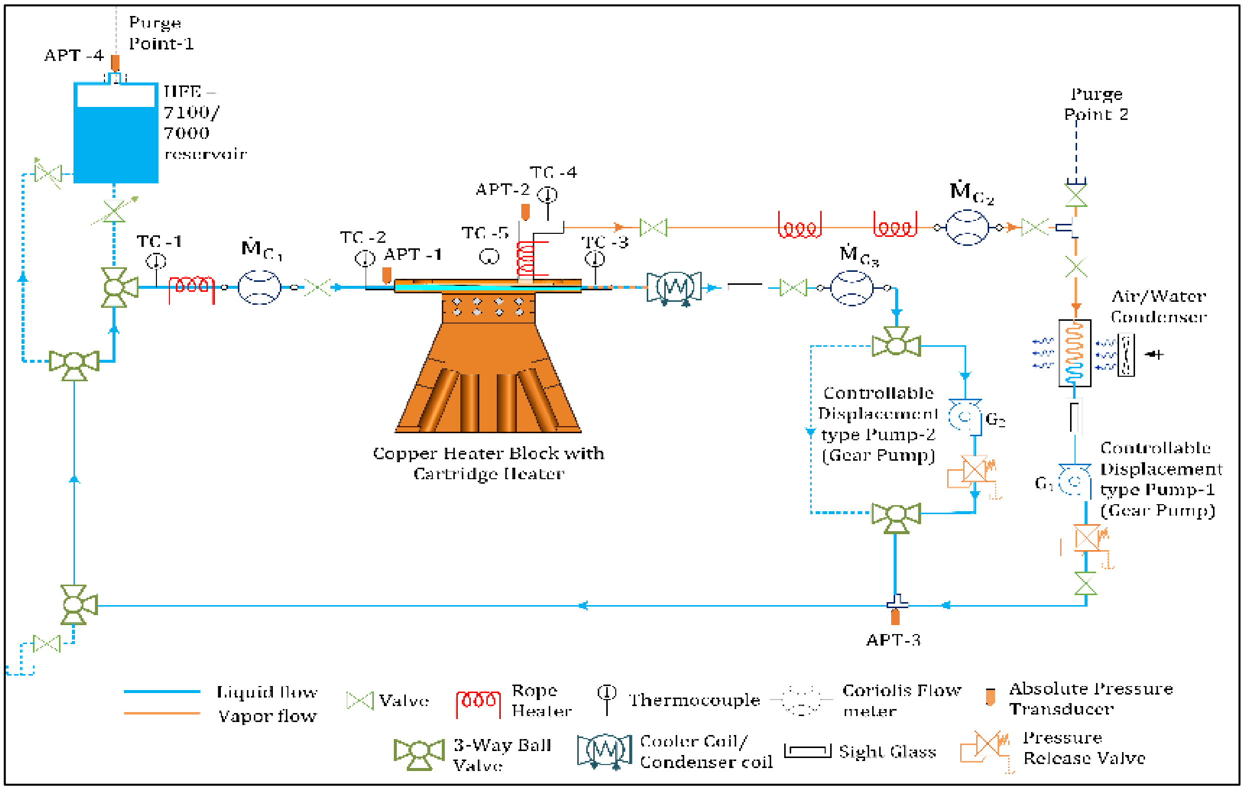
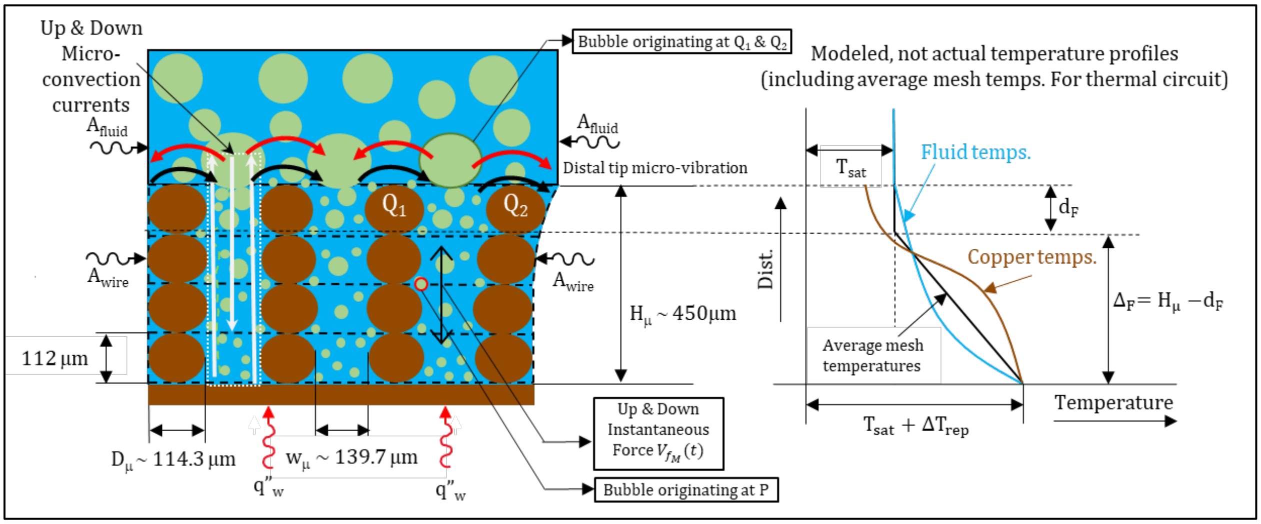


Fig. 2: *The flow-loop shown above, with its displacement pumps, flow-meters and automated flow-control strategy, suppresses most known flow-instabilities, subject to proposed increase in CHF.*



(a) **(b)**

***Fig. 3**: **(a)** Tip-vibrations and bubbling mechanisms in the heated and acoustically excited mesh zones. The in-phase and out-of-phase tip vibrations are respectively indicated by black (at frequency f_M) and red (at frequency f_P) arrows. **(b)** Experimentally inferred "temperature versus distance" variations within the mesh: for the copper, the fluid, and the matrix. Micro-vibrations caused by mesh-sized bubbling mechanisms at controlled ejection rates are present within the depicted sub-cooled zone of thickness d_F. This, in turn, significantly enhances micro-nucleation rates within the superheated mesh (zone of a thickness Δ_F).*

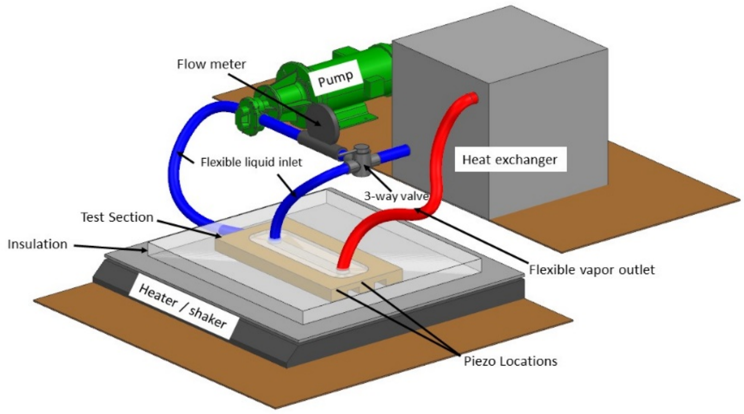


Fig. 4*: The Piezo-enhanced pool-boiling experiments' results can be obtained on laboratory table (heater not mounted on a shaker, being tested) and the results obtained can be compared with multi-g environment results obtained after mounting the heater on a vibration-table (available at Mich-Tech through one of the Co-PIs).*

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