Title: SYSTEM AND METHOD OF IMPROVED MICRO CHANNEL PERFORMANCE

Abstract: A micro-channel cooler apparatus generally includes one or more micro-channel cooler layer(s) adapted to be coupled with a heat generating surface, one or more acoustic transducers coupled with the one or more micro-channel cooler layers, and a signal generator coupled with the acoustic transducers that provides signals to the acoustic transducers to provide isolation at the micro-channel cooler layer(s). The isolation frequency and power may be selected based on a channel size of the one or more micro-channel cooler layers to promote nucleation of bubbles in a coolant fluid that flows through the one or more micro-channel layers.
SYSTEM AND METHOD OF IMPROVED MICRO CHANNEL PERFORMANCE

BACKGROUND

[0001] The operation of high-performance electronic systems (e.g. computers, RF electronics and solid state lasers) are currently limited by thermal management issues. There is a need to maintain these devices within their acceptable operating range while removing heat in excess of 1kW/cm² flux and 1kW/cm³ heat density as well as hot spot mitigation above 5 kW/cm² [DARPA-BAA-12-50]. All this must be accomplished with a minimum amount of size, weight and power consumption added to the overall system. Many speculate that these high heat fluxes can only be dissipated if both the sensible and latent heat can be accessed through two phase, micro fluidic cooling system. Moreover, the addition of bubbles to an otherwise laminar flow will add desirable turbulent mixing to enhance the local heat transfer coefficient.

[0002] Micro channel coolers operate by allowing high conductivity materials (e.g. copper, diamond etc.) to transfer the heat from the chip over a volume in as uniform temperature profile as possible. The more uniform the temperature profile within the solid volume of the cooler, a maximum utilization of the entire convective heat transfer surface can be obtained. The solid material of the cooler is embedded with micro channels to transfer the heat from the material into a flowing liquid and away from the chip. D.B. Tukerman conducted a numerical optimization of these channels and found that milli or micro channel widths with heights equal to 10 times the standard width maximized heat removal in single phase flows. In a single phase region, heat removal involves sensible heat only, which for water is 4.18 J/°C. For example, for every gram of water within the micro channel, 4.18 J will be removed for each degree of coolant heating. Unlike single phase operation where higher flow rates yield high heat transfer coefficients, access to phase change or latent heat enhances heat transfer in two phase flow. Thus, as coolant flow rate decreases, more energy will have been transferred to a single unit mass of coolant allowing a fraction of the liquid to be converted to gas (termed quality).

[0003] Figure 1 depicts a variation of heat transfer coefficient for low values of quality and mass flux, G. In this case, the water temperature remains the same, but the heat absorbed
vaporizes the water. The energy required to vaporize water is 2676 J/g. Thus, observing the same 1 gram of water as before but assuming 10% of the water is vaporized, one would achieve 267 J of heat removal. Therefore, the potential enhancement of operating micro channel coolers even in a low quality region is 64 times better. State-of-the-Art micro channel coolers have obtained heat flux capabilities above 100 W/cm²; thus, two phase operation will mitigate the 5kW/cm² hot spot requirements projected in the future.

[0004] Four critical engineering problems must be overcome to make two phase operation reliable. First, the nucleation of bubbles in specific regions is desirable to ensure transition to two phase flow; however, the surface roughness of these channels is less than 2% of the channel width (i.e. 100 to 500 nm) often causing the system to be superheated as no nucleation sites exist. Second, microfluidic flows are dominated by surface tension forces making bubble removal from the wall difficult. When bubbles are not removed effectively, a gaseous insulating layer will form that degrades the performance for heat dissipation. Third, bubbles that are removed or translated downstream are in close proximity and will, thereby, rapidly coalesce raising the pressure requirements to drive the flow, and eventually causing dry out or channel blockage. This is demonstrated in Figure 2, which depicts pressure drop as a function of capillary number showing flow regimes with a channel height of 200 microns. Finally, the total lifetime of these systems is limited by corrosion and erosion problems.

[0005] Bubble nucleation or the onset of stable cavitation by acoustic fields is well established. The onset of bubble formation is a function of the operating frequency, intensity of the pressure field, vapor pressure of the solution and predominance of available nucleation sites. Other experiments have demonstrated the ability to translate this to confined micro channels. As acoustic fields are applied to liquid media, a phenomena of acoustic streaming can be observed especially under high intensity isonations. Energy from the acoustic emission is absorbed by the fluid and translated into forward fluid motion. Several researchers have reported attempts to remove bubbles from micro channel surface via acoustic streaming but the efficiency of this process is very low, much less than 1%.
Previously, efforts established that air bubbles rising in water exposed to low intensity acoustic fields can shift the mean bubble size by rectified mass transfer.

[0006] The potential mechanisms for bubbly flow management are numerous. Many previous literary observations discuss condensation, fracture and splitting of bubbles using electric fields, hydrodynamic shear gradients, and acoustic forcing. Additionally, acoustic fields producing streaming has been studied as a mechanism for enhancing heat transfer. The electric field required to split 500 μm bubbles is on the order of 35 kV; thus, has limited applications in many industrial settings especially with conductive liquids. The hydrodynamic shear gradient option is difficult to achieve in low Reynolds number applications like those discussed above. Thus, the acoustic forcing option appears to be the most diverse in application, but the majority of the literature in this area is directed to theoretical/analytical exploration of the process or experiments that utilize high power conditions which are unlikely to be adopted by commercial applications. Absent in the microchannel heat exchanger literature is utilization of more subtle bubble management techniques like rectified heat and mass transfer.

**SUMMARY**

[0007] This Summary is provided to introduce a selection of concepts in a simplified form that are further described below in the Detailed Description. This Summary, and the foregoing Background, is not intended to identify key aspects or essential aspects of the claimed subject matter. Moreover, this Summary is not intended for use as an aid in determining the scope of the claimed subject matter.

[0008] In at least one embodiment, a micro-channel cooler apparatus is provided. The apparatus generally includes one or more micro-channel cooler layers adapted to be coupled with a heat generating surface, at least one acoustic transducer coupled with the one or more micro-channel cooler layers, and a signal generator coupled with the at least one acoustic transducer and configured to provide signals to the at least one acoustic transducer to provide isonation at the one or more micro-channel cooler layers. According to some embodiments, the isonation frequency and power are selected based on a channel size of the one or more micro-channel cooler layers. For example, the isonation frequency may be selected to
promote nucleation of bubbles in a coolant fluid that flows through the one or more micro-channel layers. In some embodiments, a frequency of a signal from the signal generator is selected to be a frequency resonant to a vapor bubble equivalent to 1/2 to 1/3 the smallest channel dimension of the one or more micro-channel cooler layers. The acoustic transducer(s) may be configured to transmit longitudinal acoustic waves into the micro-channel cooler layers, or may be configured to transmit shear acoustic waves into the micro-channel cooler layers.

[0009] In some embodiments, an acoustic amplifier may be coupled between each of the acoustic transducers and the micro-channel cooler layer(s). Such an acoustic amplifier may be a horn amplifier, for example. The apparatus may also include an impedance matching circuit coupled between the each acoustic transducer and an amplifier coupled with the signal generator. The impedance matching circuit may include, for example, a coil transformer and/or an inductor. In some embodiments the acoustic transducer(s) may be coupled with micro-channel cooler layers through a mechanical coupling, such as glue, a clamp, or a bolt, for example.

[0010] The signal generator, in some embodiments, may provide a continuous wave excitation to the acoustic transducer(s). The continuous wave may include a continuous sine wave, saw tooth or square wave, for example. In other embodiments, the signal generator may provide an intermittent excitation to the acoustic transducer(s). Such intermittent excitation may include, for example, an intermittent pulse, or an intermittent sine wave, saw tooth or square wave. A voltage applied to each acoustic transducer may be, in some embodiments, between 100 and 300 volts, peak-to-peak, from a continuous wave signal generator, and up to 400 volts peak-to-peak, from a pulse signal generator. In still other embodiments, the signal generator may include a pulse transformer that provides peak signals of up to 1000 Volts. The signal generator may include, for example, a high voltage pulse transformer driven by low voltage pulse trains from timer or operational amplifier circuit.

[0011] These and other aspects of the present system and method will be apparent after consideration of the Detailed Description and Figures herein. It is to be understood, however, that the scope of the invention shall be determined by the claims as issued and not by whether
given subject matter addresses any or all issues noted in the Background or includes any features or aspects recited in this Summary.

DETAILED DESCRIPTION

[0012] Embodiments are described more fully below with reference to the accompanying figures, which form a part hereof and show, by way of illustration, specific exemplary embodiments. These embodiments are disclosed in sufficient detail to enable those skilled in the art to practice the invention. However, embodiments may be implemented in many different forms and should not be construed as being limited to the embodiments set forth herein. The following detailed description is, therefore, not to be taken in a limiting sense.

[0013] In various embodiments of the present technology, improvement of micro channel cooler performance is attained through isonation. In some embodiments, an acoustic transducer, or array of acoustic transducers, will be rigidly affixed to one or more layers of a micro channel cooler. Affixation could be in the form of a mechanical coupling, such as with glue, a clamp, a bolt, or a connection through an acoustic amplifier such as a horn. A signal to the transducer can be either a continuous or intermittent sine wave, saw tooth or square wave, or a pulse. In some embodiments, the signal will need to be amplified. Impedance matching will, in various embodiments, also be done between the amplifier and the transducer either by a coil transformer and/or inductor. Frequency of the applied signal will be a function of channel dimensions. Some embodiments perform optimally at frequencies resonant to the vapor bubble equivalent to 1/2 or 1/3 the smallest channel dimension. The applied voltage has been run from 100 V_{pp} to 250 V_{pp} in continuous mode or 400 V_{pp} in pulse mode. Pulse transformers producing peak signals of 1000 V are also applicable as these devices are small in size while still producing effective stimulus to the transducer.

[0014] With reference now to Figure 3, an example of a micro-channel cooler apparatus is discussed. The apparatus generally includes one or more micro-channel cooler layers 305 adapted to be coupled with a heat generating surface 310, one or more acoustic transducer 315 is coupled with the micro-channel cooler layer(s) 305, and a signal generator 320 is coupled with the acoustic transducer(s) 315 and configured to provide signals to the acoustic
transducer(s) 315 to provide isonation at the micro-channel cooler layer(s) 305. According to some embodiments, the isonation frequency and power are selected based on a channel size of the one or more micro-channel cooler layers. For example, the isonation frequency may be selected to promote nucleation of bubbles in a coolant fluid that flows through the micro-channel layers 305. In some embodiments, a frequency of a signal from the signal generator 320 is selected to be a frequency resonant to a vapor bubble equivalent to 1/2 to 1/3 the smallest channel dimension of the micro-channel cooler layer(s) 305. The acoustic transducer(s) 315 may be configured to transmit longitudinal acoustic waves into the micro-channel cooler layer(s) 305, or may be configured to transmit shear acoustic waves into the micro-channel cooler layer(s) 305.

[0015] In some embodiments, an acoustic amplifier 325 may be coupled between each of the acoustic transducer(s) 315 and the micro-channel cooler layer(s) 305. Such an acoustic amplifier 325 may be a horn amplifier, for example. The apparatus may also include an impedance matching circuit 330 coupled between the each acoustic transducer 315 and an amplifier 335 coupled with the signal generator 320. The impedance matching circuit 330 may include, for example, a coil transformer and/or an inductor. In some embodiments the acoustic transducer(s) 315 may be coupled with micro-channel cooler layer(s) 305 through a mechanical coupling, such as glue, a clamp, or a bolt, for example.

[0016] The signal generator 320, in some embodiments, may provide a continuous wave excitation to the acoustic transducer(s). The continuous wave may include a continuous sine wave, saw tooth or square wave, for example. In other embodiments, the signal generator 320 may provide an intermittent excitation to the acoustic transducer(s). Such intermittent excitation may include, for example, an intermittent pulse, or an intermittent sine wave, saw tooth or square wave. A voltage applied to each acoustic transducer 315 may be, in some embodiments, between 100 and 300 volts, peak-to-peak, from a continuous wave signal generator, and up to 400 volts peak-to-peak, from a pulse signal generator. In still other embodiments, the signal generator 320 may include a pulse transformer that provides peak signals of up to 1000 Volts. The signal generator 320 may include, for example, a high
voltage pulse transformer driven by low voltage pulse trains from timer or operational amplifier circuit. Such a configuration is illustrated in FIG. 4.

According to one embodiment, a glass-covered channel 300 µm deep by 1 cm wide was milled in a 1 cm thick, 10 cm by 10 cm aluminum plate with embedded heaters. Water was pumped by a Watson Marlow peristaltic pump through the channel at a flow rated between 2 and 10 mL/min. Bubbles formed as the mean coolant temperature approached boiling (e.g. coolant in close contact to heated surface could be boiling while the mean fluid temperature is below boiling). When channel flow was observed restricted by dry out or partial blockage, a 28kHz, 150 volt acoustic field was applied. The transducer was in contact with the unheated side of the aluminum plate and in close proximity to the cooling channel, was driven by sine wave, and the effect on channel flow was recorded using a digital microscope video recorder.

Three micro channel coolers were constructed: a milli channel, micro channel and one only used in the pulsing experiment. The channel attributes are summarized as follows:

<table>
<thead>
<tr>
<th></th>
<th>H, µm</th>
<th>W, mm</th>
<th>L, mm</th>
<th>Dₜ, µm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milli Channel</td>
<td>330</td>
<td>20</td>
<td>24</td>
<td>64</td>
</tr>
<tr>
<td>Micro Channel</td>
<td>20</td>
<td>0.2</td>
<td>50</td>
<td>40</td>
</tr>
<tr>
<td>Pulsed Trans.</td>
<td>25</td>
<td>0.250</td>
<td>50</td>
<td>45</td>
</tr>
</tbody>
</table>

For all testing, insonation was done using bolt-clamped Langevin transducers from Steiner & Martins having resonances of 28 kHz and 120 kHz and constructed from SM 118 ceramic material having a Curie temperature of 300 C. The signal to the transducer was generated by a Leader LAG-120B then amplified by a Crest Vs 1100 audio amplifier operated in the bridged mode. Impedance matching to the 35 Ohm (resonant) resistance of the transducer is done with a 4:1 coils power transformer. Further impedance tuning is accomplished with a 3 mH inductor in series with the load.

Temperature measurements were accomplished using K-type thermocouples with welded junctions. K-type thermocouples were chosen for accuracy and small size, and other
measurement techniques and sensors may be used, as will be readily recognized by one of skill in the art. Thermocouples were connected to an Omega Engineering OMR 6018 data acquisition module communicating with a LabView interface that decodes the multiplexed channels, displays the real-time values and logs the data to an ASCII text file. Calibration of the DAQ is accomplished using a Transmation 1045 SN calibrator to accurately produce the 0-55 mV range signals needed by the DAQ. The DAQ automatically generates the cold junction compensation. The logged data was read and processed by MatLab.

[0021] A Watson-Marlow peristaltic 2 channel pump, model Alita 400, was employed to displace non-circulating, plain water through the test heat exchangers at rates ranging from 2-4 mL/min.

[0022] Heat exchangers with hydraulic diameters of 64 \( \mu \text{m} \) (fixture 1) and 2 \( \mu \text{m} \) (fixture 2) were insonated at different flow rates and frequencies. Input power was always maximized to assure insonation of the flow through the connection to the radiating transducers.

[0023] The thermal resistance was computed from:

\[
R_{Th} \left( \frac{W}{\text{m}^2 \cdot \text{K}} \right) = \frac{\Delta T_{e} \left( \text{K} \right)}{\dot{q} \left( \text{W/m} \right)}
\]  

(1)

\( \Delta T_{e} \) is the temperature difference across the interface between the heated billot and the microchannel heat exchanger, \( \dot{q} \) is the heat flux input to the exchanger computed from:

\[
\dot{q} = h \Delta T_{e}
\]  

(2)

Where \( h \) is the laminar flow, constant wall heat transfer coefficient, \( A \) is the channel area and \( \Delta T_{e} \) is the temperature gain of the coolant passing through the exchanger.

[0024] The heat flux dissipated by radiation and conduction is assumed to be nearly constant over an individual data set but may vary among data sets accounting for the unforced thermal resistances at the same flow rate being different.

[0025] Surface tension is well known to dominate the behavior of fluids within micro fluidic devices. A parametric study was first conducted in a milli channel cooler that had higher surface tension effects than bulk flow bubbles explored previously, but less influence than
micro channel coolers. This milli channel cooler also had dimensions that were consistent with the frequencies investigated previously. The cooler was constructed from a 3 mm brass plate with 2 mm coolant entrance and exit ports. A top brass plate 0.4 mm thick was press-bonded using cyanoacrylate to minimize joining thickness. The dimensional resonant frequencies for height and width were 24 kHz and 6 kHz, respectively. Heat absorption was monitored by measuring the mean fluid temperature when in contact with a heater held at constant heat flux (ie., maintaining constant input electrical power from a variac and monitored by a wattmeter). Thermal contact between heater and the exchanger was maximized by the use of Active Silver Ceramique heat sink compound.

[0026] The coolant was preheated water. Preheating insured two phase operation within the cooler without driving heat block temperatures above the Curie temperature of the transducer. K-type thermocouples were bead welded then placed to monitor heater body temperature, heat exchanger case temperature and coolant exit temperature. The PZT transducer was driven by continuous sine wave signals in the range 5-100 kHz and 100-300 volts. This was accomplished by connecting the 2 Vpp output signal from a Leader LAG 120B signal generator to a bridge-mode Crest Vs 1100 audio amplifier. The 8 Ω output impedance of the amplifier was transformed to the near 35 Ω input impedance (at resonance) through a 1:4 windings power transformer which also increased the output voltage. To compensate for the transducer capacitance, a 2.5 mH inductor was placed in series with it.

[0027] As passage size reduces and bubbles shrink, the capability of surface tension to dampen out affects increases; thus, a similar yet smaller parametric study as described above was conducted on a channel cooler with dimensions 1/10* those previously investigated. The cooler was constructed from a 3.3 mm etched brass plate with 2 mm coolant entrance and exit ports. The dimensional resonant frequencies for height and width were 326 kHz and 32.6 kHz, respectively. Heat absorption was monitored by measuring the mean fluid temperature when in contact with a heater held at constant heat flux (ie., maintaining constant input electrical power from a variac and monitored by a wattmeter). Thermal contact between heater and the exchanger was maximized by the use of Active Silver Ceramique heat sink compound. A 120 kHz Langevin transducer was driven by a 200 volt sine wave at 39 and 80 kHz.
[0028] Continuous wave excitation from amplification of signals from a sine wave generator by an audio amplifier according to some embodiments may include equipment that is relatively expensive, large in size and audio amplifiers may not be intended for use above 20 kHz even though it has been found that such amplification can be achieved for limited durations up to 100 kHz. In industrial practice, according to some embodiments, such as illustrated in Figure 4, the heat exchanger may be excited with high-voltage, very short duration pulses to provide similar results to continuous wave excitation.

[0029] This embodiment is designed for pulsing from 1 to 5 pulses per second. To accomplish this, an elementary transducer pulse generator has been constructed and shown in FIG. 4. In this device, a 555 integrated circuit timer generates a 12 Vp-p high impedance square wave pulse train having on and off times and duty cycle determined by the resistance values, R1 and R2 and the capacitor, C1. These contribute according to:

\[
I = \frac{i}{0.693 \cdot (R_1 + 2 \cdot R_2) \cdot C_1} \tag{3}
\]

\[
t_{on} = 0.693 \cdot (R_1 + 2 \cdot R_2) \cdot C_1 \tag{4}
\]

\[
t_{off} = 0.693 \cdot R_2 \cdot C_1 \tag{5}
\]

where \( f \) is the frequency and \( R_1, R_2 \) and \( C_1 \) are components shown in the electrical schematic above. The timer pulse train opens and closes contacts in a pc board mounted relay. If the output pulse train fails to operate the relay contacts, it may need to be amplified by a 741 operational amplifier, or use an intermediate 2N-2441 high speed switching transistor. Impedance boosting of the timer wave train was unnecessary. The opening and closing of the relay contacts shorts the gate of a high voltage SCR to its cathode which immediately turns on the SCR, discharging a high-voltage pulse capacitor through an impedance matching (to the transducer) resistor. When the positive pulse from the timer passes, the relay contacts close, the gate is no longer shorted to the cathode, and the SCR turns off. When the SCR is in the off state, high dc voltage from the supply appears simultaneously on the anode of the SCR and on one side of the high voltage capacitor which is storing the energy for making output pulses.
[0030] Input high voltage of the order of 400-1000 Vdc can be obtained by a commercial device, or it can be produced by transforming 120 Vac mains to the desired high voltage ac, then rectified and filtered.

[0031] Short pulses have high frequency components as seen in a Fourier transformation of the pulse shape. In order for pulses to effectively drive a 28 kHz ultrasonic transducer they must have a high voltage magnitude and be very short duration. As the duration shortens, higher frequency components are produced. It is for this reason that an SCR is used to switch the charge storage on the capacitor, instead of a transistor switch, which cannot activate fast enough for the needed high frequency components. This can be seen in the Fourier transformation of a much longer test pulse plotted in Fig 5.

[0032] Figure 5 depicts a Fourier analysis of pulse shape; (left) long duration test pulse as determined by the value of pulse capacitor, (center) dft of pulse (right) dft of same pulse but occurring 10 times faster. A pulse lasting 20 ms distributes most of its energy below 250 Hz. If this same pulse shape happened in a tenth of the time (ie 2 ms), then this energy distribution extends to 2500. Thus, in order to get sufficient energy into a 28 kHz transducer, the pulse must happen on the order of 20 micro seconds. This requires a low value, high voltage pulse capacitor, a high supply dc voltage and a very fast switching time.

[0033] The insonated channel flow visualization film pictures establish that 20 W insonation applied to the channel removes larger bubbles and vapor blocks in less than 1 second after the application of the acoustic field, as seen in Figures 6A through 6C, which depict images extracted from video of an insonated small channel. Figure 6A is an image of the small channel before insonation, Figure 6B is an image of the small channel less than one second after insonation is initiated, and Figure 6C is an image of the small channel, in which small bubbles remaining after insonation may be observed. These observations verify that the largest bubble sizes could be managed. As seen in Figure 6C, larger bubbles have been reduced to smaller ones at the limit of resolution.

[0034] Evaluations of various embodiments, including a milli and a microchannel heat exchanger, were performed at the strong resonant frequencies of ultrasonic transducers to determine if an improvement in heat exchanger performance by insonation would be
detected. The evaluations recorded heater, exchanger case and coolant temperatures (in and out) as a function of time as the exchanger was operated at various flow rates, and was intermittently insonated. Power input to the heater was controlled and monitored.

[0035] The radiating ultrasonic transducer used for the milli exchanger embodiment was a 28 kHz Langevin, while a 120 kHz Langevin was used for the micro exchanger. The reason for switching to the higher frequency transducer to insonate the microchannel heat exchanger is that it is a better match for acoustic power transfer to the smaller hydraulic micro channel. The frequencies of operation of the two radiating transducers were determined by intermediate resonances of these transducers which would support power transfer from the Crest audio amplifier whose cutoff frequency is normally 20 kHz.

[0036] According to some examples, two data analysis methods were employed: one examined the temperature profiled of the difference between the heater and the exchanger case as a function of the coolant temperature within the saturation state of the coolant. The second analysis method looked at the centroids of the set of thermal resistances when forced and unforced as a function of flow rate and insonation frequency.

[0037] Figures 7A through 7F depicts profiles of the difference of heater and exchanger temperature as a function of coolant temperature when the state of the coolant in the micro channel is under the saturation dome. Plots are for the example described above for flow rates of 2-6.2 mL/min, and insonation of 28 and 58 kHz.

[0038] Figure 8 depicts profiles of the difference of heater and exchanger temperature as a function of coolant temperature when the state of the coolant in the micro channel is under the saturation dome. Plots are for the example described above for a flow rate of 4 mL/min, and insonation of 39 and 80 kHz.

[0039] The following table depicts a summary of profile results plotted in the Figures 7-8.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Frequency kHz</th>
<th>Rate mL/min</th>
<th>$\Delta T_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>7A</td>
<td>58</td>
<td>2</td>
<td>$+4/-1$</td>
</tr>
<tr>
<td>7B</td>
<td>28</td>
<td>3</td>
<td>$-3/-3$</td>
</tr>
<tr>
<td>7C</td>
<td>28</td>
<td>4</td>
<td>$+5$</td>
</tr>
</tbody>
</table>
The result of thermal resistance analysis on the experimental data is presented in Figures 9-10. The points plotted are the centroids of the sets of forced and unforced data which is useful to consolidate the trends of these sets but which has the disadvantage of hiding the magnitude of the best results contained in the set. This is illustrated by the centroid thermal analysis of the 5-100 kHz survey data given. The thermal resistance improvement of the entire set is very small, < 1%, but this averaging over all results masks a 63% improvement at the very onset of boiling shown, 88.2°C. Figure 9 illustrates thermal resistance of survey, for the higher flow example described above. Figure 10 illustrates the best case detail contained in centroid of Figure 9.

The coolant temperature shown was made in the rubber tubing exit flow from the exchanger approximately 10 cm from the exit which allowed the coolant to cool from the 94.6°C boiling point for Denver, Colorado. Another explanation for the lower coolant temperature is thermocouple calibration. With this in mind, the lower coolant water temperatures identify the beginning of boiling as correspondence with visual inspection of vapor generation in the clear parts of the tubing confirmed.

Figures 11 and 12 plot the thermal analysis data sets for insonating fixture described above having a higher flow, namely the milli channel exchanger arranged in increasing flow rate. The sets noted A were made with the high frequency transducer which would make a difference in transducer/exchanger contact. The sets noted B all used the low frequency transducer and were done in almost identical conditions. The thermal resistance improvement of these points is plotted in the Figure 12.

The profile of thermal resistance improvement is shown in Figure 12. It is seen that a peak improvement takes place around 3.6 mL/min. This is consistent with the previous
thermal profile results. 28 kHz insonation will shrink bubbles smaller than 0.2 mm in diameter. The channel height of fixture 1 is 0.3 mm.

[0044] Figure 13 presents the results using an order of magnitude smaller heat exchanger. The height of this exchanger is only 0.020 mm corresponding to a bubble radius of 0.010. The resonant frequency of this size vapor bubble is 3.26/0.010 or 326 kHz. It was not possible to irradiate this exchanger at an efficient frequency. However, insonating it at 39 and 80 kHz show the thermal resistance approaching an improvement. This may be the result of the 80 kHz operating on vapor shapes spanning a fraction of the width of the channel which is 0.2 mm. At one point, 89.3°C, the improvement is 5%.

[0045] Figure 14 depicts heat flux out of the 25 g exchanger after heating then cooling (separated from the heater) with and without pulsed insonation. Coolant is ethanol having a boiling point of 78°C; pulses are 400 Vdc, 5 microsecond duration repeating at 4 Hz generated from the prototype transducer driver. The heat exchanger tested had a hydraulic diameter of 0.045 mm. Note the temperature measured is the case, not the coolant.

[0046] The insonated channel flow visualization film pictures establish that 20 W insonation applied to the channel reduces the size of bubbles and removes vapor blocks very rapidly. It is seen in the picture immediately after insonation that the larger bubbles have been significantly reduced in size rather than completely swept away as might be the case if the dominant mechanism were acoustic streaming. The observed reduction in size is consistent with the hypothesis that insonation near and above bubble resonant size can significantly shrink them. These preliminary observations did not attempt to quantify flow rates, frequencies or channel dimensions that produce best results.

[0047] In order to qualify and quantify the benefit of insonating micro channel heat exchangers, fixtures described above were studied under controlled conditions of flow rate and insonation frequencies but no attempt was made to determine thresholds of acoustic power which result in exchanger performance improvement. This because (a) the apparatus employed for the testing used commercial audio amplifiers impedance-matched to the transducer but still relatively inefficient for best transfer of acoustic power into the exchanger, (b) the attachment between radiating transducer and exchanger was always
problematic, and would sometimes loosen during the test and (c) there was always a phase difference of at least 45 degrees between voltage and current into the transducer further limiting power transfer. For these reasons, the signal to the transducer was always maximized at transducer resonance points.

[0048] The first test fixture, having a higher flow rate, was better matched to the insonation frequencies from the high-power, project Langevin transducers which have design resonant frequencies of 28 and 120 kHz. Testing with the first fixture began with a broad survey over frequency at a fixed flow rate. It then continued with studies at fixed frequencies for various flow rates. It was found that a maximum benefit approaching 16% improvement in thermal resistance was found at 3.6 mL/min. The best benefit gain of over 60% was seen in the broad survey at 4 mL/min but at an unknown frequency. The benefits all occurred just at the onset of boiling.

[0049] Testing the second test fixture described above, a micro channel heat exchanger was done using the higher frequency transducer at a fixed flow rate of 4 mL/min and insonation frequencies of 39 and 80 kHz. As expected, these frequencies were too low to produce a benefit, but the 80 kHz showed a significant improvement over insonation at 39 kHz indicating the 80 kHz was beginning to operate on vapor objects larger than channel height. This is another indication that bubble size management is the operative mechanism and not simply vibration of the walls shedding bubbles attached by surface tension or sweeping them away from acoustic streaming.

[0050] The pulsing experiment performed on the 40 µη hydraulic diameter micro channel produced a 3X heat flux improvement. It is thought that this was due to the small hydraulic diameter and small surface area of this exchanger coupled with the ability of the high voltage pulsing circuit to generate high frequency components affecting the bubble size within the 25 micron channel height. This benefit also occurred at the onset of boiling.

[0051] The experimental results support the hypothesis that insonation can improve heat flux dissipation, but only under a range of conditions. It has been found that insonation at frequencies near the resonance of bubbles smaller than the height of the micro channel generally improves heat removal. The best performance enhancement is observed in the low
quality region well way from dry out. In the single phase region, insonation appears to add heat to the system through absorption of acoustic energy faster than subcooled bubble nucleation subtracts.

[0052] It is believed that this benefit results from insonation retarding bubble growth in the exit section of the channel allowing bubbles already formed to exit the channel with their entrained latent heat. Conversely, without insonation, bubble coalescence can occur leading to slug and annular flow. It does not appear that this enhancement is primarily a result of acoustic streaming or vibration of the walls, although these mechanisms may operate in flow regimes not studied. The evidence against these mechanisms being primary is that the beneficial affects observed were all associated at the onset of boiling, occurred only at flow rates around 3.6 mL/min and at a frequency matching interior bubble sizes of around one-half to two-thirds channel height. If streaming and wall vibration were dominant, then the affect would be more generalized.

[0053] Although the effects of rectified diffusion occur rapidly (within a few thousand cycles as established by modeling), the reestablishment of large bubble flow resistance requires minutes. This suggests that a duty cycle at a very low frequency (4 Hz was used in this research), and perhaps even as reduced as 0.001%, using a pulsed signal would achieve similar results to the continuous application of an acoustic field.

[0054] Although the technology been described in language that is specific to certain structures, materials, and methodological steps, it is to be understood that the invention defined in the appended claims is not necessarily limited to the specific structures, materials, and/or steps described. Rather, the specific aspects and steps are described as forms of implementing the claimed invention. Since many embodiments of the invention can be practiced without departing from the spirit and scope of the invention, the invention resides in the claims hereinafter appended. Unless otherwise indicated, all numbers or expressions, such as those expressing dimensions, physical characteristics, etc. used in the specification (other than the claims) are understood as modified in all instances by the term "approximately." At the very least, and not as an attempt to limit the application of the doctrine of equivalents to the claims, each numerical parameter recited in the specification or claims which is modified by the term "approximately" should at least be construed in light of
the number of recited significant digits and by applying ordinary rounding techniques. Moreover, all ranges disclosed herein are to be understood to encompass and provide support for claims that recite any and all subranges or any and all individual values subsumed therein. For example, a stated range of 1 to 10 should be considered to include and provide support for claims that recite any and all subranges or individual values that are between and/or inclusive of the minimum value of 1 and the maximum value of 10; that is, all subranges beginning with a minimum value of 1 or more and ending with a maximum value of 10 or less (e.g., 5.5 to 10, 2.34 to 3.56, and so forth) or any values from 1 to 10 (e.g., 3, 5.8, 9.9994, and so forth).
What is claimed is:

1. A micro-channel cooler apparatus, comprising:
   one or more micro-channel cooler layers adapted to be coupled with a heat generating
   surface;
   at least one acoustic transducer coupled with the one or more micro-channel cooler
   layers; and
   a signal generator coupled with the at least one acoustic transducer and configured to
   provide signals to the at least one acoustic transducer to provide isonation at the one or more
   micro-channel cooler layers.

2. The apparatus of claim 1, wherein the isonation frequency and power are selected
   based on a channel size of the one or more micro-channel cooler layers.

3. The method of claim 1, wherein the isonation frequency is selected to promote
   nucleation of bubbles in a coolant fluid that flows through the one or more micro-channel
   layers.

4. The method of claim 1, wherein a frequency of a signal from the signal generator
   is selected to be a frequency resonant to a vapor bubble equivalent to 1/2 to 1/3 the smallest
   channel dimension of the one or more micro-channel cooler layers.

5. The method of claim 1, further comprising an acoustic amplifier coupled between
   each of the at least one acoustic transducer and the one or more micro-channel cooler layers.

6. The apparatus of claim 5, wherein the acoustic amplifier comprises a horn
   amplifier.

7. The apparatus of claim 1, further comprising an impedance matching circuit
   coupled between the each acoustic transducer and an amplifier coupled with the signal
   generator.
8. The apparatus of claim 7, wherein the impedance matching circuit comprises one or more of a coil transformer or an inductor.

9. The method of claim 1, wherein each of the at least one acoustic transducer is coupled with the one or more micro-channel cooler layers through a mechanical coupling selected from one or more of glue, a clamp, or a bolt.

10. The apparatus of claim 1, wherein the signal generator provides a continuous wave excitation to the at least one acoustic transducer.

11. The apparatus of claim 10, wherein the continuous wave comprises a continuous sine wave, saw tooth or square wave.

12. The apparatus of claim 1, wherein the signal generator provides an intermittent excitation to the at least one acoustic transducer.

13. The apparatus of claim 12, wherein the intermittent excitation comprises an intermittent pulse, or an intermittent sine wave, saw tooth or square wave.

14. The apparatus of claim 1, wherein a voltage applied to each acoustic transducer is between 100 and 300 volts, peak-to-peak, from a continuous wave signal generator.

15. The apparatus of claim 1, wherein a voltage applied to each acoustic transducer is up to 400 volts peak-to-peak, from a pulse signal generator.

16. The apparatus of claim 1, wherein the signal generator comprises a pulse transformer that provides peak signals of up to 1000 Volts.
17. The apparatus of claim 1, wherein the signal generator comprises a high voltage pulse transformer driven by low voltage pulse trains from timer or operational amplifier circuit.

18. The apparatus of claim 1, wherein each of the at least one acoustic transducer is configured to transmit longitudinal acoustic waves into the one or more micro-channel cooler layers.

19. The apparatus of claim 1, wherein each of the at least one acoustic transducer is configured to transmit shear acoustic waves into the one or more micro-channel cooler layers.
FIG. 7C

FIG. 7D
FIG. 7E

FIG. 7F
FIG. 8

$D_h = 0.64$ mm

FIG. 9
FIG. 10

FIG. 11
D_h = 0.64 mm, 28 kHz, milli exchanger

FIG. 12

D_h = 0.02 mm

FIG. 13
FIG. 14
## INTERNATIONAL SEARCH REPORT

**International application No.**
PCT/US2013/060701

### A. CLASSIFICATION OF SUBJECT MATTER

- **IPC(B):** F28D 15/00-06; SF 07/00, 02, 13/00, 10; G06F 01/16, 20; H01L 23/34, 42, 427, 46, 467, 473; H05K 07/20 (2013.01)
- **USPC:** 165/1-04.29

According to International Patent Classification (IPC) or to both national classification and IPC

### B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

- IPC(B): F28D 15/00-06; SF 07/00, 02, 13/00, 10; G06F 01/16, 20; H01L 23/34, 42, 427, 46, 467, 473; H05K 07/20 (2013.01)
- USPC: 165/1-04.1 1-104.13, 104.19, 104.21, 104.23-104.29, 104.31-104.34; 361/699, 700

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

- CPC: F28D 15/00-06; F28F 07/00, 02, 13/00, 10; G06F 01/16, 20; H01L 23/34, 42, 427, 46, 467, 473; H05K 07/20 (2013.01)

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

- Orbit, Google Patents, Google, Google Scholar

### C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
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<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
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<td>1-4</td>
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<td>US 2010/0109481 A1 (BUCCAFUSCA) 06 May 2010 (06.05.2010) entire document</td>
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<td>Y</td>
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<tr>
<td>Y</td>
<td>CN 101640487 A (CHUNJIANG et al) 03 February 2010 (03.02.2010) see machine translation</td>
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- "&" document member of the same patent family

**Date of the actual completion of the international search**
19 December 2013

**Date of mailing of the international search report**
10 JAN 2014

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PCT/US2013/060701

Form PCT/ISA/210 (second sheet) (July 2009)