SINGLE-PHASE HEAT TRANSFER ENHANCEMENT TECHNIQUES IN MICROCHANNEL AND MINICHANNEL FLOWS

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ABSTRACT
The single-phase heat transfer enhancement techniques are well established for conventional channels and compact heat exchangers. The major techniques include flow transition, breakup of boundary layer, entrance region, vibration, electric fields, swirl flow, secondary flow and mixers. In the present paper, the applicability of these techniques for single-phase flows in microchannels and minichannels is evaluated. The microchannel and minichannel single-phase heat transfer enhancement devices will extend the applicability of single-phase cooling for critical applications, such as chip cooling, before more aggressive cooling techniques, such as flow boiling, are considered.

INTRODUCTION
Microchannel and minichannel cooling has made the high heat flux removal in such applications as microprocessor cooling, cooling of high power electronic equipment, compact heat exchangers, and even compact fuel cells possible. The small hydraulic diameter increases the heat transfer coefficients in these passages, Kandlikar (2002).

The fundamental understanding of microchannel flows and heat transfer mechanisms in microchannels is critical to the development of devices that utilize these channels for cooling passages. The combination of microfluidics and microscale heat transfer presents new sets of engineering problems and opportunities.

The application of microchannels to cool microprocessors is of particular interest. The majority of researchers working in this field realize the benefits of two-phase flow systems to meet the cooling requirements for high heat fluxes. The heat transfer improvement gained by a two-phase system (given the same heat flux and mass flux) is well documented in conventional sized channels, and current research is ongoing in the microchannel region. However, the total pressure drop, pumping requirements and system complexity are greatly increased in a two-phase flow system.

The application of single-phase heat transfer enhancement in conventional sized passages has been a widely accepted and developed area of research. It is often regarded as a discipline with the majority of techniques and mechanisms being well understood. However, several researchers have renewed the interest in heat transfer augmentation. The combination of different techniques and the need for further understanding of the fundamental mechanisms involved will provide further augmentation. However, the use of these conventional scaled techniques needs to be carefully evaluated and verified for their applicability to microchannel and minichannel flows.

The combination of the two fields of microchannel flows and heat transfer enhancement creates the potential to develop a single-phase cooling device that can compete with a comparable two-phase cooling system without the high-pressure drop penalty or pumping power requirements.

OBJECTIVES OF PRESENT WORK
The present work focuses on reviewing conventional single-phase heat transfer enhancement techniques. The possibility of applying these techniques with the addition of some novel applications in microchannel and minichannel flow is discussed.

OVERVIEW OF CONVENTIONAL SINGLE-PHASE ENHANCEMENT TECHNIQUES
Study of heat transfer augmentation began as early as in the 1920s and the work continues to the present day. In the
Some of the basic techniques used for the passive phase flow augmentation will be discussed in this section. Microchannels and minichannels have classified the augmentation techniques into two categories, passive and active.

In addition, Bergles has presented reviews of this topic in (1997, 1999, 2002). In his latest work, Bergles (2002) presents the fourth generation of heat transfer enhancement using a combination of different techniques. He suggests that the field can be extended and heat transfer coefficients further increased by combining different individual techniques. The use of multiple techniques in single-phase flows is an attractive possibility.

Balaras (1990) reviewed augmentation techniques and classified them as surface, fluid, combined and compound methods. The surface methods involved modifications to the heated surface such as extended surfaces, roughened surfaces, swirl-flow devices, and surface vibration. The fluid methods involved external fluid vibration, additives and electrostatic forces. The combined and compound methods use suction, injection and a combination of the other methods.

Based upon other research and their own, Tao et al (2002) have presented three possible mechanisms for the single-phase heat transfer enhancement. These three mechanisms are: 1) Decreasing the thermal boundary layer, 2) Increasing flow interruptions, and 3) Increasing the velocity gradient near the heated surface. It is the manipulation of these three mechanisms that results in heat transfer augmentation.

The channel classification used for the present study was presented in Kandlikar and Grande (2002). A conventional sized flow passage has a hydraulic diameter larger than 3.0 mm. A minichannel passage has a hydraulic diameter between 3.0 mm and 200 μm. A microchannel has a hydraulic diameter less than 200 μm. The classification is meant for a guideline in describing the size of a flow passage. The present work will focus on applying heat transfer augmentation in conventional sized passages to the minichannel and microchannel passages. The following discussion closely follows the classification of enhancement techniques as outlined by Bergles (1996).

A summary of the techniques discussed is presented in Table 1. The techniques are described according to their application in a conventional channel, minichannel, and microchannel.

**PASSIVE ENHANCEMENT TECHNIQUES FOR MICROCHANNELS AND MINICHANNELS**

The passive enhancement techniques used in single-phase flow augmentation will be discussed in this section. Some of the basic techniques used for the passive enhancement include flow disruption, secondary flows, surface treatments, and entrance effects. Several of these techniques can be easily implemented into a microchannel or a minichannel.

**Surface Roughness**

One passive technique is to alter the characteristics of the heated surface. This method reduces the thermal boundary layer thickness and also aids in early transition into turbulent flow. The conventional way to alter the surface is to increase the roughness of the surface. The effective roughness \( \varepsilon/D \) ratio is increased to create a boundary layer influence. The roughness ratio can be very large in a microchannel. Therefore, the roughness structure could approach the channel diameter and cause adverse flow behavior. This issue is a very active area of current research. Kandlikar et al (2003) studied the effect of surface roughness in a minichannel flow. They determined that the \( \varepsilon/D \) ratio has a bigger effect in smaller diameter channel than the same \( \varepsilon/D \) ratio in a conventional channel. Further information on the microfluidic physics is required for implementation.

Champagne and Bergles (2001) presented an interesting work to develop a variable roughness enhancement structure. The idea utilized an insert constructed from a shape memory alloy (SMA), specifically Nickel Titanium. As the change in temperature increased, the insert would expand and increase the heat transfer enhancement. This concept could be expanded to minichannels and microchannels. Some SMAs could be inserted into the channels to provide a similar function.

**Flow Disruptions**

The inclusion of flow interruptions is perhaps the most attractive technique to incorporate. The flow disruptions provide increased mixing and also can serve to trip the boundary layer causing flow transition. In conventional sized passages, the flow interruption can be achieved using flow inserts, flow disruptions along the sidewalls, and offset strip fins.

These techniques are strong candidates for implementation in minichannels. The ability to manufacture smaller diameter wire has progressed enough to manufacture a thin wire, such as those for surgical applications, and insert a tightly coiled wire into a minichannel.

The use of flow inserts in a microchannel maybe impractical due to the space requirements. The microchannel dimensions prove to be the limiting factor for the wire diameter currently available. Although, the basic concept in the flow inserts can be applied to microchannels. The flow disruption technique could find easy integration into microchannels using carefully constructed geometries. The feature size and geometry of objects improve as the achievable critical dimension is decreased. The sidewalls of the microchannel could contain flow obstacles that disrupt the boundary layer.
Table 1. Summary of Enhancement Techniques for Use in Microchannels and Minichannels.

<table>
<thead>
<tr>
<th>ENHANCEMENT TECHNIQUE</th>
<th>CONVENTIONAL $D_h &gt; 3$ mm</th>
<th>MINICHANNEL $3$ mm $\geq D_h &gt; 200$ $\mu$m</th>
<th>MICROCHANNEL $200$ $\mu$m $\geq D_h &gt; 10$ $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Passive Techniques</strong></td>
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<tr>
<td>Surface Roughness</td>
<td>Roughness structure remains in boundary layer; provides early transition to turbulence</td>
<td>Use different surface treatments, roughness structures can remain in boundary layer and protrude into bulk flow</td>
<td>Can achieve with various etches; roughness structures may greatly influence flow field</td>
</tr>
<tr>
<td>Flow Disruptions</td>
<td>Using twisted tape, coiled wires, offset strip fins; fairly effective</td>
<td>Can extend conventional methods here; offset strip fins, some twisted tapes, small gauge wire</td>
<td>Can use sidewall or in channel; optimize geometry for minimal impact on flow</td>
</tr>
<tr>
<td>Channel Curvature</td>
<td>Not practical due to large radius of curvature; has been demonstrated in $D_h = 3.33$ mm</td>
<td>More possible than conventional; incorporate return bends for compact heat exchangers</td>
<td>Most practical; achievable radius of curvature; large number of serpentine channels</td>
</tr>
<tr>
<td>Re-entrant Obstructions</td>
<td>Effect not as prevalent; bulk flow reaches fully developed flow quickly; harder to return flow to developing state</td>
<td>Can incorporate structures to interrupt flow; header design could contribute to pre-existing turbulence</td>
<td>Short paths make for dominate behavior; can incorporate opportunities to maintain developing flows</td>
</tr>
<tr>
<td>Secondary Flows</td>
<td>Flow obstructions can generate secondary flows; combination of inserts and obstructions</td>
<td>Could use jets to aid in second flow generation; combination of inserts and obstructions</td>
<td>Can fabricate geometries to promote mixing of fluid in channel</td>
</tr>
<tr>
<td>Out of Plane Mixing</td>
<td>Not very effective; space requirements prohibitive</td>
<td>Possible use; three dimensional mixing may not be that effective</td>
<td>Greatest potential; fabricate complex 3D geometries very difficult</td>
</tr>
<tr>
<td>Fluid Additives</td>
<td>PCMs dominate</td>
<td>PCMs possible; fluid additives possible</td>
<td>Fluid additives; mico- and nanoparticles possible</td>
</tr>
<tr>
<td><strong>Active Techniques</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibration</td>
<td>Surface and fluid vibration utilized currently</td>
<td>Possible to implement; can use in compact heat exchangers</td>
<td>External power is a problem; integrate piezoelectric actuators</td>
</tr>
<tr>
<td>Electrostatic Fields</td>
<td>Electrohydrodynamic forces currently used; integrated electrodes</td>
<td>Could be easier to integrate into compact heat exchanger; external power not as problematic</td>
<td>Can integrate electrodes into channel walls; power consumption problematic</td>
</tr>
<tr>
<td>Flow Pulsation</td>
<td>Established work showing enhancement</td>
<td>Can implement in compact heat exchangers fluid delivery</td>
<td>Possible to implement, could make fluid delivery simpler</td>
</tr>
<tr>
<td>Variable Roughness Structures</td>
<td>Difficult to integrate very small variable structures into a conventional channel</td>
<td>Difficult to integrate into compact heat exchangers</td>
<td>Possible to integrate; piezoelectric actuators change roughness structure</td>
</tr>
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</table>

Figure 1 shows sidewall obstacles in a microchannel. The triangular obstruction seen in Fig. 1a would serve to cause some swirl flow. The steps shown in Fig. 1b would break up the boundary layer and change the thermal and hydraulic gradients.

Another possibility is using flow obstacles in the bulk area of the microchannel. Figure 2 shows some channel flow obstructions. Figure 2a shows some obstructions with simple rectangular geometries. Figure 2b shows some obstructions with circular geometries. The heights of these structures could vary to increase the secondary flows in the flow field. As the achievable critical dimensions in lithography are reduced, a more refined circular profile can be achieved. These geometries can be optimized and intermixed to achieve the maximum amount of heat transfer enhancement with the lowest pressure drop penalty.

**Channel Curvature**

Several researchers have demonstrated that heat transfer enhancement can be achieved by having a curved flow path. The traditional parabolic velocity profile is skewed due to the additional acceleration forces. This causes the angle between the gradients to decrease and facilitate enhancement.

Sturgis and Mudawar (1999) demonstrated the enhancement in a curved channel. The radius of curvature was 32.3 mm and the channel had a cross section of 5.0 x 2.5 mm. The resulting hydraulic diameter is 3.33 mm. The
enhancement reached as much as 26% for the curved channel versus a straight channel.

Fig. 1: Sidewall flow obstructions in a microchannel. a) triangular obstructions, b) square obstructions.

Fig. 2: Flow obstructions in the channel. a) simple rectangular geometry, b) circular profile.

This technique is not really practical in a large sized conventional passage. The application is a possibility in a minichannel for using return bend and such for compact heat exchangers. However, the greatest potential lies in a microchannel. The radius of curvature can be on the order of a few millimeters to centimeters but considered to be large compared to the channel diameter. The compact nature of the microchannel flow network could allow for a serpentine flow channels to utilize the curvature enhancement. This concept can be seen in the work involved in fabricating a microsystem gas chromatography column.

**Re-entrant Obstructions**

The entrance region of channels can also provide heat transfer enhancement. There are a few researchers that have reported the enhancement gained in the entrance region of a microchannel, Gui and Scaringe (1995). This technique could also find application in minichannels. However, the short lengths and low Reynolds numbers found in microchannel flows seem to be more appropriate. Gui and Scaringe (1995) reported heat transfer enhancement in microchannel heat sinks. The hydraulic diameters range from 221 μm to 388 μm. They suggested that the high heat transfer coefficients resulted from the decreased size, entrance effects, pre-existing turbulence at the inlet, and wall roughness.

The short lengths in a microchannel could allow a design to build in entrance spaces in the flow network. The sudden expansion and contractions would generate entrance effects. This would cause the flow to be in a perpetual state of development and allow for heat transfer enhancement. Figure 3 demonstrates such an arrangement. The cavities could also be used for pressure measurements and possible mixing sites.

Fig. 3: Entrance spaces in a microchannel flow network.

Fig. 4: Re-entrant structures included in a microchannel.

Another possibility in utilizing entrance effects is shown in Fig. 4. In this case, a re-entrant structure is incorporated in the channel. The structure could eventually
be optimized to provide the maximum entrance effect with the minimal pressure drop. The structure can be added several times in the channel to cause continual developing flow. Similar structures could be included in a minichannel as well. However, the design of those structures might be limited to simple geometries such as orifices. However, the pressure drop penalties in these apparatuses need to be carefully evaluated.

Secondary Flows

Many researchers have demonstrated that secondary flows within the flow field provide enhancement. This can be seen in conventional channels. This technique can be applied in minichannels using offset strip fins and chevron plates and further refinement for minichannels is possible. The optimal shape and pitch of such devices can continue to improve the heat transfer enhancement.

![Fig. 5: Secondary flow channels.](image)

The generation of secondary flows or swirl flows also has potential in microchannels. The geometry of the microchannel can be manipulated to produce secondary flow. Figure 5 shows a simple geometry that can generate secondary flows. Smaller channels are added between the main flow channels. Secondary flow will move from one channel to another via these channels.

A second method for generating secondary flow comes from a conventional device. A venturi can be manipulated to generate secondary flow without external power and a major increase in pressure drop. Figure 6 shows a venturi based secondary flow apparatus. The throat area is connected to the larger area section of an adjacent microchannel. The reduction in pressure at the throat area seen from the reduction in area will draw flow in from the larger area of the adjacent channel. This technique could also be utilized to increase fluid mixing or the addition of another flow stream to the main flow stream without the need for secondary flow pumping power. Once again, the pressure drop penalties could be a limiting factor for these devices.

Out of Plane Mixing

A technique being developed to increase binary fluid mixing could also be applied to the heat transfer enhancement in microchannels. Bondar and Battaglia (2003) have studied the effect of out of plane or three-dimensional mixing of two-phase flows in microchannels. They have achieved a high degree of fluid mixing. An example of a three-dimensional twisted microchannel is shown in Fig. 7. This work could provide a path to follow for single-phase heat transfer. The rotation of the fluid will promote mixing and therefore change the hydrodynamic and thermal gradients.

![Fig. 7: Three-Dimensional Twisted Microchannel, Bondar and Battaglia (2003).](image)

Fluid Additives

The addition of small particles to the fluid can sometimes provide heat transfer enhancement. The use of small particles containing a phase change material (PCM) to achieve heat transfer enhancement has been studied. The particles begin in the solid state. As the fluid temperature increases, the particles reach their melting point and begin to melt. The latent heat of fusion involved with the melting of the PCM creates an enhancement. In other words, the effective heat capacity of the fluid has changed due to the presence of the PCM.

Hu and Zhang (2002) studied the effect of microcapsules containing a PCM. The radius of the particles used was 50 μm in a 1.57 mm radius duct. Figure 8 shows the effect of particle concentration on the heat transfer enhancement. The figure shows the degree of heat transfer enhancement versus the non-dimensionalized axial
coordinate, using the duct radius. This method works well in conventional channels. Smaller particles are being developed for use in minichannels and may possibly extended to microchannels.

Small quantities of another liquid can be added to the working fluid to achieve enhancement. The concentration of the secondary substance affects the amount of enhancement obtained. A good example is seen in Peng and Peterson (1996). They used water as the working fluid and methanol as the additive. Technically, this would be considered a two-phase mixture. However, Peng and Peterson reported the results in terms of single-phase heat transfer enhancement. The present work will also consider the mixture in such a context. It should be noted that the mixing of these additives typically does not achieve a perfect mixture. Therefore, the use of this technique can provide heat transfer enhancement in a very specific range of operation. Due to the imperfect mixture, the heat transfer coefficients can decrease.

The recent development of nanoparticles, such as those used with Microscale Particle Image Velocimetry (μPIV), provides some possibilities for microchannel heat transfer enhancement. The particles could be included to augment the heat transfer without causing a major clogging issue.

**ACTIVE ENHANCEMENT TECHNIQUES FOR MICROCHANNELS AND MINICHANNELS**

The active enhancement techniques used in single-phase flow augmentation will be discussed in this section. Generally, these techniques require additional, external input into the system. The input to the system could be in the form of power, electricity, RF signals, or external pumps.

**Vibration**

Vibration in the fluid or surface is another active technique that has been applied to conventional channel. The tubes in some conventional heat exchangers can vibrate and provide heat transfer enhancement. This technique could easily be applied to a minichannel heat exchanger. The smaller more compact nature of the tube bundles would allow for easier access for tube vibration.

Recently, Go (2003) studied the effect of microfins oscillating due to flow-induced vibration. The working fluid was air at velocities of 4.4 m/s and 5.5 m/s. A microfin array was fabricated on a heat sink. As the fluid moves over the microfins, a vibration is induced that causes heat transfer enhancement. Figure 9 shows the temperature difference for both a microfin array and a plain heat sink. It was determined that the microfins provided up to an 11.5% enhancement over a plain heat sink.

The use of conventional external vibration generators in a microchannel is impractical due to the large sizes. However, a vibrating source could be integrated in a microchannel wall. The same technology that generates piezoelectric actuators could find application here. If a piezoelectric material can be embedded, deposited, or placed to act on the microchannel walls, the piezoelectric can be made to oscillate at different frequencies. This would generate surface vibrations and cause enhancement. Figure 10 shows the piezoelectric enhanced microchannel.

![Fig. 8: Effect of concentration on single-phase heat transfer coefficient, Hu and Zhang (2002); $r_0 = 1.57\,\text{mm.}$](image1)

![Fig. 9: Effect of microfin array on heat sink temperature difference, Go (2003).](image2)

![Fig. 10: Piezoelectric enhanced microchannels.](image3)
Researchers. They have demonstrated the enhancement for conventional sized heat exchangers as well as minichannel flows. An excellent paper by Allen and Karayiannis (1995) presents a review of the literature on electrohydrodynamic enhancement. The governing equations, working mechanisms, and existing correlations are presented with some experimental work. It is concluded that the corona wind and electrophoresis contribute the most to single-phase heat transfer enhancement.

This technique could also be applied to microchannel flows. In a conventional or a minichannel application, a small insert electrode is present in the flow field. A potential is applied between the insert probe and the channel surface. The electric field that results will provide a moving corona effect and enhance the heat transfer. Figure 11 shows this arrangement for all three channel sizes: conventional, minichannel and microchannel.

Flow Pulsation

The variation of the mass flow rate through the channel can also provide heat transfer enhancement. Several researchers have demonstrated the mixing enhancement provided by a pulsating flow. Hessami et al. (2003) studied the effect of flow pulsation on a two-phase flow in a 25 mm pipe. They determined that the enhancement could be as much as 15% depending upon the frequency. This technique could be applied in a microchannel. The requirement of delivering constant mass flow rates to a cooling device could be eliminated.

Variable Roughness Structures

Another possibility exists for a variable roughness structure in a microchannel flow. With a variable roughness structure, the heat transfer enhancement could become variable as well. Piezoelectric actuators could be used to control the local surface roughness along the wall. Therefore, the heat transfer enhancement could be customized. Figure 13 shows a possible variable roughness structure using actuators of some type.

CONCLUSIONS

The following conclusions can be drawn from the present work.

- Some of the more successful enhancement techniques currently used for heat transfer augmentation have been reviewed. The applicability of single-phase enhancement techniques is evaluated for microchannel and minichannel flows.
Several passive techniques have been identified as possibilities for microchannel enhancement. The passive techniques do not rely on external power or activation. Therefore, these techniques do not have any additional power costs.

Several active techniques have been identified as possibilities for microchannel enhancement. Unfortunately, these techniques do require external power. There is a power cost that needs to be considered. This fact makes a microsystem designer carefully consider their implementation.

Pressure drop penalties and heat transfer performance of the enhancement techniques discussed in the present work need to be verified experimentally and/or numerically.

There is a great deal of research needed to bring these proposed techniques into fruition. In some cases, the technology might not be available. However, the present work is expected to serve as a road map for microchannel and minichannel heat transfer enhancement.

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>c</td>
<td>volumetric concentration of microcapsules, LL⁻¹</td>
</tr>
<tr>
<td>D</td>
<td>diameter, m</td>
</tr>
<tr>
<td>h</td>
<td>convective heat transfer coefficient, W m⁻² K⁻¹</td>
</tr>
<tr>
<td>r₀</td>
<td>duct radius, m</td>
</tr>
<tr>
<td>x</td>
<td>axial coordinate, m</td>
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Greek

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ε</td>
<td>roughness, m</td>
</tr>
<tr>
<td>η</td>
<td>degree of heat transfer enhancement, η = h/h_single</td>
</tr>
</tbody>
</table>

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REFERENCES


