[0054] Three flow patterns are commonly encountered during flow boiling in minichannels: isolated. bubble, confined bubble or plug/slug, and annular.

[0055] The effect of interfacial surface tension between phases is crucial in determining the final boiling flow regime. The presence of small nucleating bubbles, as small as 10 to 20 microns has been confirmed.

[0056] It should be noted that from a heat transfer performance standpoint, isolated bubbles are most desirable. Chedester and Ghiaasiaan (2002) cite data and previous theoretical analyses supporting the theory that bubble nucleation and evolution phenomena in microchannels are fundamentally different than in their large channel counterparts. In subcooled boiling, the velocity and temperature gradients near the walls of microchannels can be very large, and bubbles resulting from subcooled or saturated boiling can be extremely small. The occurrence of extremely small bubbles significantly impacts the various subcooled boiling processes including the onset of nucleate boiling (ONB), onset of significant void (OSV), and departure from nucleate boiling (e.g., film boiling).

[0057] The same authors (Ghiaasiaan and Chedester, 2002) also propose the hypothesis that boiling incipience in microchannels may be controlled by thermocapillary forces that tend to suppress the formation of microbubbles on wall cavities. If this were indeed the case, it would suggest that the heat transfer in microchannels, which is greatly enhanced by nucleate boiling due to the latent heat of vaporization, would actually perform worse than in conventional-sized channels. Their studies suggest that macroscale models and correlations for boiling heat transfer appear to under-predict the heat fluxes required for incipience of boiling in microtubes (defined to possess diameters in the range of 0.1 mm to 1 mm). It should be noted, among other factors, that their experiments were run in the fully turbulent regime, whereas most practical microchannel applications are operated in the laminar flow regime.

[0058] Haynes and Fletcher (2003) describe work where subcooled flow boiling heat transfer coefficients for select refrigerants in smooth copper tubes of small diameter have been investigated experimentally. The parameter ranges examined are as follows: tube diameters of 0.92 and 1.95 mm, heat fluxes from 11 to 170 kW/m^2, and total mass fluxes of 110 to 1840 $kg/(m^2\text{-}s)$. Furthermore, the range of liquid Reynolds numbers encompassed by the data set is 450 to 12,000. In their work, they encountered no evidence that convection suppresses the nucleate term nor that nucleation events enhance the convective term, even in laminar and transitional flows. However, the laminar flows, in particular, are prone to enhancement by unknown mechanism.

[0059] Prodanovic, et al. (2002) note in their experimental studies that bubble agitation is the primary heat transfer model during nucleate boiling. Agitation dissipates as the bubble travels away from the heated channel surface.

[0060] Lee et al. (2004) conducted experiments in bubble dynamics in a single trapezoid microchannel with a hydraulic diameter of 41.3 microns. The results of the study indicates that the bubble nucleation in the microchannel typically grows with a constant rate from 0.13 to 7.08 microns/ms. Some cases demonstrate an extraordinarily high growth rate from 72.8 to 95.2 microns/ms. The size of bubble departure from the microchannel wall is found to be governed by surface tension and drag of bulk flow (as opposed to wall shear stress) and may be fairly correlated by a modified form of Levy equation. They also maintain that the bubble frequency in the microchannel is comparable to that in an ordinary sized channel.

[0061] Thome (2004) reviews recent research in microchannel boiling. Experiments and theory on evaporation in microchannels have been reviewed. He maintains that the most dominant flow regime appears to be the elongated bubble mode that can persist up to vapor qualities as high as 60-70% in microchannels, followed by annular flow, and that the controlling heat transfer mechanism is not nucleate boiling nor turbulent convection but is transient thin film evaporation. Flow boiling heat transfer coefficients have been shown by some investigators to be dependent nearly exclusively on heat flux and saturation pressure, i.e. similar to nucleate pool boiling heat transfer and only slightly dependent on mass velocity and vapor quality. However, more recent tests demonstrate a mass velocity and vapor quality effect, supporting the hypothesis that boiling heat transfer is controlled by slug flow or thin film boiling.

[0062] Stability of Flow

[0063] Stability of boiling flow in a microchannel is an issue of great concern. Since no comprehensive theory for onset of instability yet exists, it is primarily studied through flow pressure fluctuations and visualization. Heat transfer is much less efficient for unstable flow because of many factors including unsteadiness in the flow patterns, formation of film boiling, reverse flow, and poor flow distribution. Below are citations of the existing prior art literature on this subject. Brutin et al. (2003) investigated two-phase flow instabilities in convective boiling taking place in narrow rectangular microchannels. Hydraulic diameter was 889 microns and channel length was 200 mm. The experiments were conducted at mass fluxes of 240 $kg/(m^2\text{–}s)$ and heat fluxes ranging from 3.3 to 9.6 W/m^2. All these conditions exhibited vapor slug formation which blocks the two-phase flow and pushes the two-phase flow back to the flow entrance. Based on their experimental observations, they establish a criterion for steady state flow as low fluctuation amplitude variations in measured flow pressure of less than 1 kPa and a characteristic oscillation frequency of a ratio less than 20 (peak amplitude to noise amplitude).

[0064] Wu et al. (2004) describe a series of experiments carried out to study different boiling instability modes of water flowing in microchannels at various heat flux and mass flux values. Eight parallel silicon microchannels, with an identical trapezoidal cross-section having a hydraulic diameter of 186 micron and a length of 30 mm, were used in the experiments. When the wall heat flux was increased from 13.5 to 22.6 W/cm^2 and the time average mass flux of water was decreased from 14.6 to 11.2 $g/cm^2\text{-}s$, three kinds of unstable boiling modes were observed in the microchannels:

[0065] Liquid/two-phase alternating flow (LTAF) at low heat flux and high mass flux

[0066] Continuous two-phase flow (CTF) at medium heat flux and medium mass flux, and

[0067] Liquid/two-phase/vapor alternating flow (LTVAF) at high heat flux and low mass flux.