PARTIAL BOILING IN MINI AND MICRO-CHANNELS

RELATED APPLICATIONS

[0001] This application claims the benefit of priority provisional application Ser. No. 60/624,860 filed Nov. 3, 2004.

[0002] This invention relates generally to methods, apparatus and systems (where systems are constituted by apparatus containing a fluid or fluids and may be further characterized by parameters such as pressure, temperature, etc.) in which there is partial boiling of a liquid in a mini-channel or microchannel. A minichannel has at least one dimension of 10 mm or less. A microchannel has at least one dimension of 2 mm or less, in some embodiments 1 mm or less, in some embodiments 0.5 mm or less, and in some embodiments in the range of 0.01 to 2 mm. While a mini and microchannel generally have the dimensions described above, in some preferred embodiments, a microchannel has a diameter of $D_h<2$ mm, where Dh is the hydraulic diameter, and a mini-channel is defined as having a diameter D_h from 2 to 10 mm.

Theory of Partial Boiling

[0003] Boiling is known as a highly efficient heat transfer mechanism that provides high heat flux density based on surface area and volume. There are several different boiling regimes including low vapor quality flow, nucleate boiling, film boiling and transition boiling. Nucleate boiling is mostly found in the industrial applications. Boiling can take place at heat transfer surface both in fluid flow (flow boiling) and fluid pool (pool boiling) or in the volume of the fluid (flash). Through phase change of the fluid, flow boiling has the potential to achieve an isothermal heat sink in the fluid while the phase change is occurring. Flow boiling can achieve very high convective heat transfer coefficients, and that coupled with the isothermal fluid allows the heat transfer wall to remain at quasi-constant temperature along the flow direction. This is a desirable heat transfer situation for many thermal, nuclear and chemical process applications

[0004] In many chemical processes, such as an exothermic chemical reactor, the reaction rate strongly depends on the local temperature. An optimal temperature throughout the reaction zone often leads to a maximum yield, conversion and desired selectivity. Thus, boiling heat transfer is used in process control or thermal management of various reactions to maintain an isothermal thermal condition where the exothermic reaction(s) releases heat. Compared to a boiling process control, a cooling system via single-phase fluid convection generally cannot achieve a near isothermal boundary condition for the reactions without large flow rates needed to keep the stream at constant temperatures and increase the convective heat flux.

[0005] So far, boiling in microchannels has not been used in the thermal management and control of the microchannel chemical reaction processes due to various postulated or practical technical issues including the following:

[0006] 1. Flow boiling in microchannels is associated with the flow patterns different from that found in the ordinary flow channels where vapor bubbles are smaller than the channel diameters and the channel wall is generally well wetted by the liquid. The hydraulic diameter of microchannels is usually smaller than the characteristic diameter of the vapor bubbles so that due to capillary effect vapor slugs and liquid slugs consecutively flow by a fixed location of the channel (**FIG. 1**). The prediction methods and design criteria for this flow pattern are not well established.

[0007] 2. The other desired flow patterns such as bubbly flow and annular flow may only be possible in a very narrow flow parameter range or limited operation conditions or may be absent.

[0008] 3. Due to the existence of vapor slugs, local hot spot of the wall and in turn the temperature non-uniformity may occur due to the low vapor-wall heat transfer rate.

[0009] 4. Due to the existence of vapor slugs, severe flow and pressure oscillation may occur in microchannel boiling. Instability of the entire cooling system may instantly occur.

[0010] 5. The heat transfer crisis can occur even at low heat duty due to the large difference between the heat transfer coefficients by evaporation and by single-phase vapor convection. This is characterized by the critical heat flux (CHF) that may be very low and lead to non-isothermal heat transfer (**FIG. 1**).

[0011] 6. The flow distribution and manifolding are difficult in microchannel arrays with two-phase flow, while large number of integrated microchannels is usually needed for the desired process capacity.

[0012] The inventive process makes it possible to make use of flow boiling in microchannels integrated in unit operations to realize a stable isothermal boundary condition for the exothermal reaction. The reaction process can be thus thermally controlled to operate in an optimal condition.

[0013] The term "equilibrium quality X_{eq}" also known as quality or "X" is defined as:

$$X_{eq} = \frac{z \cdot q'' \cdot P}{A \cdot G \cdot h_{fg}}, \quad (1)$$

where

[0014] z[m]=The distance from the channel inlet in water flow direction (m)

[0015] q"[W/m^2]=The average channel wall heat flux

[0016] P[m]=Channel perimeter normal to the direction of flow

[0017] A[m^2]=Channel cross sectional area normal to the direction of flow

[0018] G [kg/m$^{2/}$s]=Mass flux rate through the channel cross sectional area normal to flow

[0019] h_{fg}[J/kg]=Latent heat of evaporation

The equation (1) assumes:

[0020] 1) The point of Onset of Nucleate Boiling (ONB) with X_{eq}=0 is just located at the channel inlet. In the practical operation, the water flow at inlet would be slightly subcooled due to non-condensable gas. As