As an extension of the recent work of Baldassari and Marengo, this note presents Kandlikar third number map for flow boiling in micro-channels and micro-gravity. Using several data points available in the literature, Kandlikar third number map was plotted vs. the hydraulic diameter as the characteristic dimension for flow boiling in micro-channels and micro-gravity. The ranges of the Kandlikar third number, calculated using the hydraulic diameter, are presented.

Key words: two-phase flow, flow boiling, micro-channels, micro-gravity, Kandlikar third number

In the 21st century, studies on flow boiling in micro-channels have gained significant attention in engineering community. Flow boiling in micro-channels is a necessary option for cooling high heat flux micro-devices. In recent years, there is an increasing use of micro-channels in the industry to yield compact geometries for heat transfer. Due to their large heat transfer surface area, the use of micro-channels can result in relatively high heat transfer coefficient when compared with the application at macro-scales. In many applications related to the refrigeration and air conditioning, micro-channels can be viewed as being responsible for the mitigation of environmental influences by enabling the use of smaller amounts of fluids. Also, flow boiling experiments under micro-gravity conditions are useful to understand of interfacial structures and heat transfer for the phenomena on ground in addition to their application to the innovative two-phase thermal management systems for the future space development. Recently, Baldassari and Marengo [1] presented a review article on flow boiling in micro-channels and micro-gravity. The researchers plotted maps of non-dimensional numbers employed in micro-channels flow boiling experiments in normal and in micro-gravity conditions vs. the hydraulic diameter ($d_h$) as the characteristic dimension. These non-dimensional numbers were Eotvos number ($E_0$), Weber number if total flow (liquid plus vapor) assumed to flow as liquid ($W_{LO}$), Weber number if total flow (liquid plus vapor) assumed to flow as vapor ($W_{VO}$), capillarity number if total flow (liquid plus vapor) assumed to flow as liquid ($C_{LO}$), Reynolds number if total flow (liquid plus vapor) assumed to flow as liquid ($R_{LO}$), Reynolds number if total flow (liq-
uid plus vapor) assumed to flow as vapor ($Re_{VO}$), boiling number ($BI$), Kandlikar first number ($K_1$) and Kandlikar second number ($K_2$).

In the present note, the author would like to add a map of Kandlikar third number ($K_3$) values explored in the literature on flow boiling because Baldassari and Marengo [1] presented only Kandlikar first number ($K_1$) and Kandlikar second number ($K_2$) as non-dimensional numbers relevant to two-phase studies in micro-channels. In his reply to the discussion of Awad [2], Kandlikar third number ($K_3$) was derived recently by Kandlikar [3]. The new non-dimensional constant, $K_3$ is defined as [3, 4]:

$$K_3 = \frac{\text{Evaporation momentum force}}{\text{Viscous force}}$$  

and represents the ratio of the evaporation momentum force, and the viscous force. Kandlikar [3] mentioned that this non-dimensional group $K_3$ had not been independently used yet, but it was relevant if the evaporation momentum and viscous forces were considered in a process. $K_3$ could also be represented as [3, 4]:

$$K_3 = K_1 \frac{Re_{LO}}{Ca_{LO}} = \frac{K_2}{Ca_{LO}}$$  

In his summary, Kandlikar [3] mentioned that recognizing the evaporation momentum force as an important force during the boiling process opened up the possibilities of three new relevant non-dimensional groups, $K_1$, $K_2$, and $K_3$. Any two of these groups could be represented by combining the third one with one of the other relevant non-dimensional groups $Re_{LO}$, $We_{LO}$, and $Ca_{LO}$. As a results, Kandlikar third number ($K_3$) map of data in literature can be added to the list of figures of Baldassari and Marengo [1] using the above relation. This can be done using two different ways as shown in eq. (2). First, the values of Kandlikar first number ($K_1$) are multiplied by the values of Reynolds number if total flow (liquid plus vapor) assumed to flow as liquid ($Re_{LO}$). Second, the values of Kandlikar second number ($K_2$) are divided by the values of capillarity number if total flow (liquid plus vapor) assumed to flow as liquid ($Ca_{LO}$). Figure 1 presents $K_3$ map of data in literature. Also, Kandlikar third number map of only micro-gravity literature data can be added to the list of figures of Baldassari and Marengo [1] using the above relation. This can be done using two different ways as shown in eq. (2). First, the values of Kandlikar first number ($K_1$) are multiplied by the values of Reynolds number if total flow (liquid plus vapor) assumed to flow as liquid ($Re_{LO}$). Second, the values of Kandlikar second number ($K_2$) are divided by the values of capillarity number if total flow (liquid plus vapor) assumed to flow as liquid ($Ca_{LO}$). Figure 1 presents $K_3$ map of data in literature. Also, Kandlikar third number map of only micro-gravity literature data can be added to the list of figures of Baldassari and Marengo [1] using the eq. (1) as presented in fig. 2. In figs. 1 and 2, the ranges of the Kandlikar third number, calculated using the hydraulic diameter ($d_h$) as the characteristic dimension, are presented. For $K_3$ number map of data in literature as shown in fig. 1, the maximum and minimum values of the Kandlikar third number, are obtained for Chen et al. data [13] in circular tubes with internal diameters of 1.10 and 4.26 mm using
R134a as the working fluid. For $K_3$ number map of only micro-gravity literature data as shown in fig. 2, the maximum and minimum values of the Kandlikar third number ($K_3$), are obtained for Ohta data [28] in test section of 8 mm diameter using R-113 as the working fluid.

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**Nomenclature**

$Ca$ – capillarity number, [-]

$K_1$ – Kandlikar first number, [-]

$K_2$ – Kandlikar second number, [-]

$K_3$ – Kandlikar third number, [-]

$Re$ – Reynolds number, [-]

**Subscripts**

LO – total flow (liquid plus vapor) assumed to flow as liquid

VO – total flow (liquid plus vapor) assumed to flow as vapor

**References**


