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Turbulent heat transfer analysis of supercritical carbon dioxide close to the pseudo-critical point in microchannels under non-uniform heat flux boundary conditions

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With the increasing heat flux produced by more and more compact electronics device, new technologies are studied to replace more conventional air cooling systems. Due to the good thermal properties of the carbon dioxide around its pseudo-critical point, its safety and its low cost, microchannel based heat exchanger using supercritical carbon dioxide might be a suitable alternative to reduce the power used at the pump and manage the high heat load of the new electronic devices.

This work investigates the performance of a microchannel based heat exchanger using supercritical carbon dioxide close to its pseudo-critical point as its working fluid and subject to a non-uniform heat flux boundary condition. To achieve this particular boundary condition, the heat exchanger is heated up by Joule effect through its bottom Inconel plate. The other sides of the exchanger, being made of Torlon plastic, insure a thermal insulation on three of the four sides of the channels. Two different aspects are studied. On the one hand, the turbulent heat transfer is analysed experimentally. At first in steady-state conditions, the impact of different parameters (inlet temperature, heat flux and mass flux) over the heat transfer is analysed. Then the response of the system to transient heat flux and mass flux is also experimentally tested. On the other hand, a modeling work is investigated in parallel. A model is develop at first for the steady-state heat exchange and the experimental results are used to validate the model predictions. Finally, a transient model is then developed to predict the transient heat exchange with a varying heat flux and mass flux.

First of all, experimental data were recorded with only one varying parameter (the other being as constant as possible) to determine the impact of the different parameters without the interaction of the others. In addition to the traditional heat transfer coefficient and temperature measures the results include the analysis of the buoyancy and the acceleration effect with the help of different developed criteria. It was rapidly shown that the acceleration effect was negligible in all experimental conditions used throughout this work. On the contrary buoyancy effect is present in most tests due to the high density gradient across the boundary layer. Overall, the results showed a negative effect over the heat transfer caused by a higher heat flux with a lower heat transfer coefficient, higher temperatures and higher buoyancy effects. On the opposite, the mass flux was shown to improve the results with much higher heat transfer coefficients, lower temperatures and lower buoyancy effects. The inlet temperature showed to be the parameter with the smallest impact over the performances. The general transient response of the system was shown to be fast with the possible apparition of some local effects during a heat flux variation. However the lack a data points makes it impossible to confirm those without further testing.

Finally, a heat exchanger model is developed using the electrical analogy for both the steady-state and transient conditions. The results are in good agreement with the experimental work as more than 87% of the experimental tests are predicted with a mean absolute percentage error lower than 20%. The model predictions show a possible increase of the average heat transfer coefficient over the channel up to 15% with an optimized inlet temperature (considering that the pseudo-critical point is always reached in the exchanger). The mass flux is shown to have the highest impact over the heat transfer, a 0% increase of the mass flux leads to a 100% increase in the heat transfer coefficient and a quadratic decrease of the buoyancy effect. The model also shows number as high as $6000\text{W/m}^2\text{K}$ over the whole channel in a realistic simulation of electronics cooling with a relatively low mass flux. Moreover, the transient model showed a really fast response of the system to both a varying heat flux and a varying mass flux.

In conclusion, the microchannel based heat exchanger using supercritical carbon dioxide shows promising results but needs some further research notably in the transient part.