Understanding the bimodal oscillation of droplet generation in microfluidic junctions

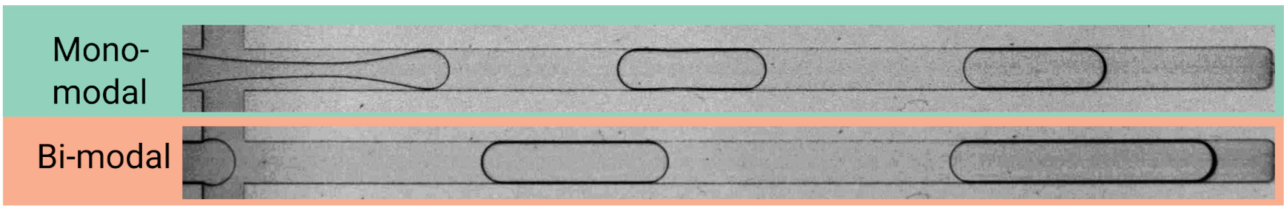
Highly constricted systems produce well-ordered flows: cars on orderly city streets, trains in a railway system, and people moving in well-designed city municipalities. Consider a fluid flowing through a conduit that is about ten times smaller than a normal straw. A higher pressure is needed to blow the fluid out (a miniaturization of a traffic jam) but the flows are regular and predictable due to the dominant wall effect and viscosity, a measure of fluid resistance. In more complex systems, such as the flows of two or more non-miscible fluids through a junction of multiple microchannels (microfluidic junctions), the flow patterns resulting from the junction may vary. Nevertheless, it is generally understood that the output of such a system is constant as long as the input is constant, e.g., monodisperse droplet production from a constant input of two immiscible flows. However, highly constricted systems may also produce unexpected results, e.g., two droplet sizes produced from a constant input, as described below.

It was observed that a slight modification to the microfluidic junction was able to break the predictability of the viscous flow pattern, such that it is possible to have droplet formations with bimodal oscillation, producing two distinct droplet sizes from constant input. The finding contradicts the common paradigm and leaves the author wondering: What conditions are required for such an oscillation? Could further geometry modification induce oscillation with more than two modes (n-mode)? The interaction between the two immiscible fluid interfaces and the geometrical constriction generates an unexpected bimodal droplet formation that is not fully understood. Further investigation is required to answer the questions above.

Another related preliminary finding shows an increase in flow rate range in which droplets are generated due to the addition of a wider channel downstream of the junction. Interestingly, the addition of a wider channel downstream bears a resemblance to the commonly used “flow-focusing” junction but with a little longer constriction. However, the increase in droplet-production range due to the longer constriction has not been described yet, and it remains a question how different downstream channel shape and position could alter the resulting flow pattern. The more general question is what geometrical factors that are important in promoting droplet generation, and how these geometries differ from the commonly used microfluidic junctions. Thus, the aim of this study is to understand the bimodal oscillation of droplet formation in microfluidic junctions and the effect of various geometrical constrains on the generated flow patterns.

Those questions will be answered through experimental observation and theoretical work. Experiments will be conducted in a diverse set of microfluidic junctions, with different geometry and a wide channel size range — from millimeters to micrometers. Various liquid pairs and a wide range of fluid flow conditions will be used to elucidate the effect of viscosity, surface tension and geometrical constriction on the droplet formation. Various parameters, e.g., droplet size, droplet-tip position, etc., will be measured by image analysis. The theoretical work aims to establish the relations between the measured parameters, flow conditions and microfluidic junction geometrical aspects. The resulting theoretical work will be verified with the experimental measurement.

The comprehension gained from this study holds high significance as it can aid users in determining the optimal microfluidic junction for their requirements and potentially open the door for novel applications. For example, the bimodal droplet generator allows the spatio-temporal control of dual-size droplet generation without any additional of active control elements. The production of dual size droplets may immediately benefit the study of single-cell analysis, i.e., it allows the single-cell analysis to be performed in two sizes of droplet simultaneously.



Experimental images showing droplet formation in a “cross-junction” microfluidic junction. Top: droplet formation with mono-modal that produces single droplet size. Bottom: bimodal droplet formation, with the resulting two different droplet sizes. It is commonly understood that there can be only single mode oscillation of droplet generation in such simple systems. However, the preliminary result shows there can be multiple mode oscillation that allows the production of multiple droplet sizes.