Chapter 6

Conclusions & recommendations

Discovery, they believe, is inevitable

Ian Malcolm, in Michael Crichton's *Jurrassic Park*

The main objective of this research was to identify the modification of bubbling phenomena with electrostatic potential and then tame the chaos of bubbling with the newly identified variable.

Electrostatic potential was identified as a bifurcation variable, which could be used to modify the periodicity of the bubbling. Extensive 3-d bifurcation plots revealed that the effect of electrostatic potential on the period of formation in comparison to flow-rate is similar. Surface contour plots, which mapped frequency of bubbling as a function of flow-rate and electrostatic potential suggested that effect of electrostatic potential on the bubbling frequency was non-linear with relatively greater effect on the bubbling at higher flow-rates. Electrostatic potential was discovered to modify bubbling to an extent where it could be used for control.

Flow control, which was carried out by previous researchers, was unsuccessful mainly because of the lack of fast valves. It was also felt that the dynamics of the change in the nozzle

chamber supply pressure to change in flow-rate also presents a challenge to using flow-rate as the manipulated variable. Electrostatic potential was identified as a control handle with better response dynamics (as compared to flow-rate) and thus was conjectured to promise relatively *'crisper'* control. The effect of electrostatic potential on bubbling regimes was studied at different flow parameters and the non-linear gain characteristics of electrostatic potential were identified. The bubbling regime at higher electrostatic potential was found to be more sensitive to unit change in voltage than at lower voltages. This investigation of chaos in bubbling led to development of several data analysis and automation tools (Sarnobat, 1999, 2000).

A real time bubbling regime identification module in LabView was successfully implemented to achieve simultaneous feedback control and real time return map updating with a moving window history. Regime control was demonstrated targeting a specific bubbling regime for period-1 and period-2. Electrostatic potential was successfully used as the manipulated variable to track a constant average bubbling frequency with flow-rate changes as the disturbance. Future work can include integration of the two control modules for maintaining a constant bubbling frequency within a constant regime. This is presently limited by sufficiently fast computing resources.

OGY control was attempted with partial success, limited by the small gain provided by the physical equipment (± 490 volts). It is recommended that the same experiment be repeated with a higher voltage swing (± 5000 volts) if a voltage *'rippler'* with a response time of greater then 40Hz can be built. It is also recommended that multivariate control with voltage and flow rate both as control variables is carried out with voltage as the fine-tuning parameter and flow control providing the rough tuning parameter. A real time OGY control module needs to be investigated into which can do dynamic fixed-point calculations and controller coefficient updates. This currently is limited by computer speed and memory. But that should not be a tight

constraint in the future. Alternatively, an OGY controller tuning search module can be implemented to fine tune the controller after the rudimentary manifold calculations. This is currently limited by the problem of running the column continuously for long periods of time, which causes an increase in the conductivity of glycerol with time.

Data analysis tools developed with MATLAB™ used multi-variate statistical techniques like principal component analysis to analyze bubbling. Wavelets and multi-scale methods were used with promising success and its potential as a chaos analysis tool are stressed.

Finally in the regime of bubbling and associated phenomena, in the present study the effects of electro-hydrodynamic (EHD) flows were assumed to be negligible and were not studied. Future study of bubbling can include study of EHD flows induced with different shapes of nozzles, various chamber sizes and changing the nozzle diameter. Changing the liquid selection is another avenue of investigation. The application of electrostatic potential to inverse spraying in liquid-liquid system holds bright prospects in light of the this research.