Latent heat recovery from a counterflow direct contact falling droplet heat exchanger

by Stephen Edward Izbicki

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering
Montana State University

Abstract:
Heat recovery in one configuration of a direct contact counterflow, falling droplet heat exchanger (DCHX), from natural gas combustion products was evaluated in terms of sensible and latent effectiveness. Effectiveness was found for uniform and nonuniform water droplet streams, and high and low inlet gas humidity ratios over a range of droplet flow rates and inlet gas temperatures. A droplet generator was built and tested to characterize droplet uniformity under various operating conditions. Uniform droplets were produced by vibrating the droplet generator at a fixed frequency and amplitude. Results agree well with those predicted by Rayleigh's theory on the instability of liquid jets. A stream of nonuniform drops, having standard deviations two to four times higher than the uniform stream, was produced when the generator was not vibrated. Preliminary heat exchange studies show single phase energy and two phase mass balances within about 6 %, indicating reasonable accuracy of temperature and flow measuring apparatus. DCHS effectiveness, defined in sensible heat recovery terms, is. shown to be further from its thermodynamic limit than that of a standard (no direct contact) counterflow heat exchanger in the same range of NTU values. A modified effectiveness is defined which includes the latent heat availability of the inlet gas stream. Modified effectiveness values were about 50% of their sensible counterparts indicating that latent heat recovery could be significantly improved.

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NOMENCLATURE

Symbol	Description
C_D	drag coefficient
C_p	specific heat, kJ/kg-°K
C_R	thermal capacitance ratio
C_d, C_∞	droplet, freestream mass concentration, kg/m³
D_{AB}	mass diffusivity, m²/s
D_d	droplet diameter, mm
d_j, d_t	jet, tube diameter, mm
F	vibration frequency, Hz
g	gravitational acceleration, m/s²
h_{fg}	latent heat of vaporization, kJ/kg
h_c, h_d	thermal, diffusion convective coefficient, W/m²-°K
k	thermal conductivity, W/m-°K
L	column length, m
NTU	number of transfer units
M_L, M_{dg}	liquid, dry gas molecular weight, kg/kg-mole
$\mathring{m}$, $\mathring{m}_{dg}$	wet, dry gas mass flow rate, kg/s
P_v	vapor pressure, kPa
q	heat transfer rate, W
R	thermal resistance, °K/W
T	temperature, °K
t_c, t_R	droplet contact, residence time, s
V	velocity, cm/s

NOMENCLATURE--continued

Symbol	Description
Greek Letters	
δ	surface tension, N/m
$\varepsilon_S, \varepsilon_L$	sensible, latent effectiveness
λ	wavelength, mm
μ	dynamic viscosity, kg/m-s
v	kinematic viscosity, m^2/s
ρ	mass density, kg/m^3
σ	standard deviation
ω	gas humidity ratio, kg_L/kg_{dg}
Non Dimensional Parameters	
Bi	Biot number, h_cL_c/k_d
Le	Lewis number, $k_g/(\rho C_p)_g D_{AB}$
Nu	Nusselt number, h_cL_c/k_g
Pr	Prandtl number, $C_p\mu/k_g$
Re	Reynolds number, VL_c/v
Sc	Schmidt number, $\mu/\rho D_{AB}$
Sh	Sherwood number, h_dL_c/D_{AB}
Subscripts	
1	DCHX inlet
2	DCHX outlet
d	droplet
dg	dry gas
g	gas
in	test section inlet

NOMENCLATURE--Continued

Symbol	Description
j	jet
L	liquid
lm	log mean
m	measured
min	minimum
nc	natural convection
opt	optimum
out	test section exit
p	predicted
r	radiative
s	inner surface
T	terminal
tot	total
∞	freestream conditions

ABSTRACT

Heat recovery in one configuration of a direct contact counterflow, falling droplet heat exchanger (DCHX), from natural gas combustion products was evaluated in terms of sensible and latent effectiveness. Effectiveness was found for uniform and nonuniform water droplet streams, and high and low inlet gas humidity ratios over a range of droplet flow rates and inlet gas temperatures . A droplet generator was built and tested to characterize droplet uniformity under various operating conditions. Uniform droplets were produced by vibrating the droplet generator at a fixed frequency and amplitude. Results agree well with those predicted by Rayleigh's theory on the instability of liquid jets. A stream of nonuniform drops, having standard deviations two to four times higher than the uniform stream, was produced when the generator was not vibrated. Preliminary heat exchange studies show single phase energy and two phase mass balances within about 6%, indicating reasonable accuracy of temperature and flow measuring apparatus. DCHX effectiveness, defined in sensible heat recovery terms, is shown to be further from its thermodynamic limit than that of a standard (no direct contact) counterflow heat exchanger in the same range of NTU values. A modified effectiveness is defined which includes the latent heat availability of the inlet gas stream. Modified effectiveness values were about 50% of their sensible counterparts indicating that latent heat recovery could be significantly improved.

CHAPTER I

INTRODUCTION

Substantial amounts of low temperature energy, with the potential to reduce fuel consumption, are being lost through combustion gas exhaust streams. Examples of such situations are industrial boilers, gas turbine exhausts, domestic hot water heaters and wood stoves. As fuel costs escalate and its availability decreases, the need for technology to recover this wasted energy will become increasingly more important. Existing recovery methods consider minimum flue gas exit temperatures to be 400-420°K. This temperature is usually limited by the need to avoid forming acidic condensate in the heat exchanger.[1,2]

Direct contact heat exchangers (DCHX) afford several advantages over conventional types. For conventional heat exchangers, the intermediate heat exchange surfaces increase thermal resistance thereby decreasing system efficiency. In addition, these surfaces are prone to corrosion and scaling which further increases thermal resistance and requires maintenance. Since the DCHX has no such surface these problems do not exist. It is estimated that heat transfer coefficients ten times higher are possible using a DCHX in favor of conventional types.[3]

This geometry is also known to be effective in removing particulate and certain water soluble gases from combustion product emissions. Fine particle collection, whose efficiency is strongly influenced by droplet Reynolds number, can be achieved with drop diameters up to .5mm falling at their terminal velocity [4]. Water soluble pollutant gases such as SO_2, NO_2 and H_2S can be removed by absorption. The driving force for this mechanism is the difference between the partial pressure of the soluble gas (pollutant) in the gas mixture and the vapor pressure of the solute gas (pollutant) in the liquid.[5] This difference is favorable for SO_2 absorbtion and moderately favorable for NO_2 and H_2S. It is assumed that in a commercially useable unit, the DCHX will be a closed system with a secondary heat exchanger. This configuration will require a filter or other purification device in the DCHX loop to remove acid and particulate buildup from the working fluid.

Although direct contact heat exchange has long been used in industry, specific data pertaining to performance is limited. Fair [6] reviews works on analysis and design of industrial DCHX's. He presents heat transfer correlations for spray column heat exchangers using hollow and solid cone spray nozzles. Drop sizes delivered from these nozzles typically vary over a wide range since they are designed to provide uniform application, not uniform drop size. Sideman and Moalem-Maron [7] examined over one hundred works published from 1922 to 1979 on condensation heat exchangers. Of the seven publications cited for dealing with droplet formity. Goren and Wilke [8] used uniformly sized Aroclor drops on which to condense steam. More recently , Sekins and Thayer [9] report heat exchanger effectiveness of around 48% for 1mm monodisperse silicon oil drops in airflow. They comment that natural breakup(no imposed oscillations) results in a wide range of small and large drops [10]. None of the above studies however, show how drop size variation influences DCHX effectiveness. Mussulman and Warrington [11] have written a computer model which shows, for a mean droplet size of 2.1mm, that reducing the size distribution from 50% to 5% increased the effectiveness of an air cooling tower by 100%.

The aim of the present study is to determine the influence changes in droplet monodispersity have on DCHX effectiveness over a range of operating conditions. It is proposed that a monodisperse droplet stream maximizes heat transfer for this configuration. Heat exchange is enhanced by the large number of small drops, increasing heat transfer surface area for a given water flow rate. For a fixed DCHX column diameter, the optimum gas flow rate is determined by the terminal velocity of the smallest drop. If this were not the case, the smallest drops would be carried out of the DCHX column by the gas stream, leading to makeup water requirements. Minimum column length is a function of droplet residence time. Large drops have comparatively low surface area to volume ratios, high Biot numbers and high terminal velocities. As a result, large drops have higher terminal velocities. As a result, large drops have higher residence times, lower contact times and lower overall heat transfer rates than smaller drops. Consequently narrowing the drop size dispersion should improve effectiveness.

The present study was carried out in two parts. First a monodisperse droplet generator was tested to characterize the size dispersion of droplets produced under various operating conditions. Next the effectiveness of a vertical tube heat exchanger, utilizing the droplet generator, was evaluated. In this configuration, a monodisperse stream of falling water droplets extracts energy from a counterflow of natural gas combustion products (see figure 1). As mentioned previously, a commercially useable unit will most likely be a closed system. However for simplicity's sake, the present DCHX system is an open one. It is shown that a nearly monodisperse droplet stream (σ=5%) can be produced by mechanically disturbing, at a specified frequency, a plate to which a group of equally spaced capillary tubes, producing jets, are attached. Conversely, a randomly sized droplet stream (σ=10-20%) will result if this disturbance is removed. Heat exchanger effectiveness was determined for the DCHX over a range of operating conditions, for uniform and nonuniform droplets, and for air and natural gas combustion products.

In light of the above discussion, it seemed logical to organize this paper in a similar manner. Therefore the remaining discussion is comprised of three parts. Chapter

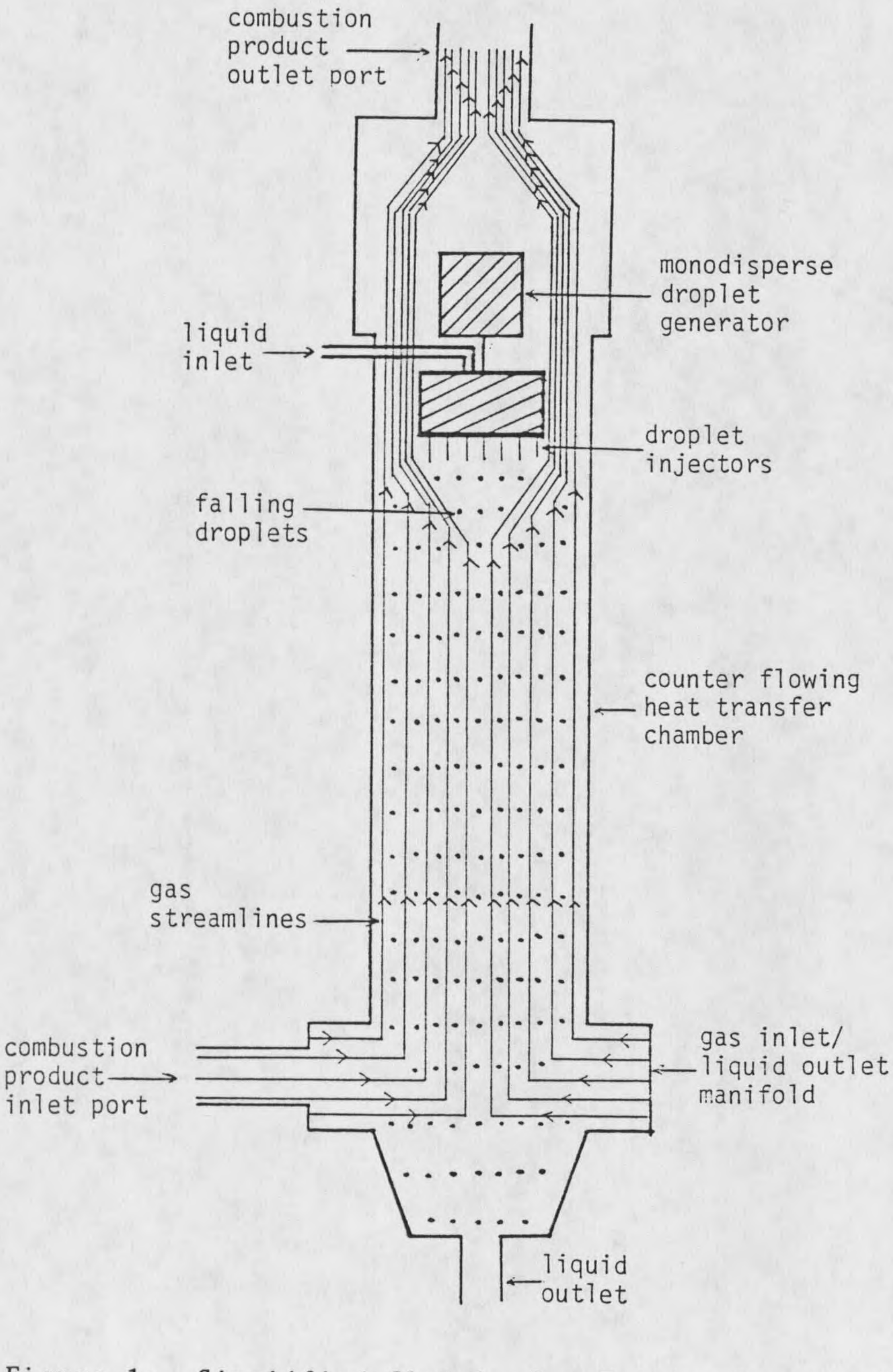

Figure 1: Simplified Sketch of a Falling Droplet DCHX

II describes techniques used in producing and measuring a monodisperse droplet stream. This includes a report of current uniform droplet production theory and the results of droplet characterization studies. In Chapter III, results from the first study are used as the basis for variations in drop size dispersion in the DCHX performance experiments. DCHX experimental apparatus and procedure are reviewed in Chapter III, along with development of the theoretical background and a discussion of pertinent results. The conclusions section, Chapter IV, is concerned with results from both the monodisperse droplet and DCHX performance studies.

CHAPTER II

MONODISPERSE DROPLET STUDY

Background

It is of critical importance in the current investigation to show that a water droplet stream of nearly uniform size and spacing is produced by axially vibrating a capillary jet. This phenomenon is well documented in the literature. Devices used to produce such a stream in this manner are based on Rayleigh's analysis on the instability of capillary jets [12] for an inviscid liquid. Rayleigh showed that the frequency of vibration which leads most rapidly to the disintegration of a liquid column is given by:

$$F_{opt}=V_j/4.508d_j \tag{2.01}$$

Rajagopalon and Tien [13] have shown that uniformly sized drops are produced over a frequency range in which column wavelength λ, varies between $3.5d_j$ and $6.5d_j$. These limits correspond closely to those found experimentally ($3.5d_j<\lambda<7d_j$) by Schneider and Hendricks [14]. Rayleigh's linearized theory predicts that the lower limit should be $\lambda_{min}=(\pi)d_j$ [9].

Linblad and Schneider [15] report that, in order to overcome viscous forces, capillary jets must have a minimum velocity to be established. This minimum is a function of liquid density, surface tension, and jet diameter. It is given by:

$$(V_{j,min})^2 = 8\delta/\rho_d d_j \qquad (2.02)$$

However Dabora [16] has found actual minimum velocities up to 35% lower than equation (2.02) predicts.

By conservation of mass, the volume of one drop equals the volume of a water column one wavelength long, from which the ratio of drop to jet diameter is found as:

$$D_d/d_j = 1.145(V_j/Fd_j)^{1/3} \qquad (2.03)$$

Results by Rajagopalon and Tien [13] showed agreement to within 3% of equation (2.03), indicating good drop uniformity with little waste due to satellite formation.

Several authors indicate that vena contracta effects at the tube exit cause jet diameters to be somewhat less than tube diameters [15,17]. Harmon [18] assumes a laminar jet velocity distribution, and by conservation of momentum determines that $d_j=.866d_t$. A study by Goren and Wronski [19] indicates that, for a parabolic velocity profile, jet diameter actually increases at low Reynolds numbers ($Re_j<17$). At higher Reynolds numbers ($17<Re_j<100$) this diameter decreases monotonically to a value slightly higher than that which Harmon predicts ($d_j/d_t=.885$). Their analysis does not however, include viscous dissipation effects. They suggest that at sufficiently high jet velocities, viscous effects cause a flatter profile, and drive the ratio d_j/d_t toward unity. Schneider and Hendricks [14] and Dabora [16] have assumed this ratio to be unity in their investigations.

Mathematical formulations describing the production of nonuniformly sized drops are sparse. Levich [20] derives an expression showing drop size, without imposed oscillations, to be of the order $D_d \sim D_{d,opt}$. $D_{d,opt}$ refers to droplets produced at the vibration frequency for maximum jet instability predicted in Rayleigh's analysis. Most of the previously cited works confirm that nonuniform droplets are produced in the absence of oscillations. They do not however, attempt to characterize the degree of nonuniformity.

Apparatus

The first step in conducting this investigation was to develop a droplet generator along with instrumentation to characterize droplet formation (see Figure 2 for schematic). Liquid at constant temperature, pressure and flow rate is delivered to the generator chamber in the following manner. Water from an isothermal source is supplied to the constant head reservoir (Figure 2) at a flow rate slightly higher than that passing through the generator chamber. Excess water is drained through the overflow outlet, providing a source of water to the capillary jets having a constant head and the proper flow rate. Jet velocities were varied by adjusting the reservoir elevation. The water source is then filtered and its temperature, flow rate and pressure are monitored immediately prior to entering the generator chamber. An oscillator-amplifier combination supplies a signal of set frequency and amplitude to the chamber by means of an MB Electronics PM500 Vibramate Excitor. Diagnostics to

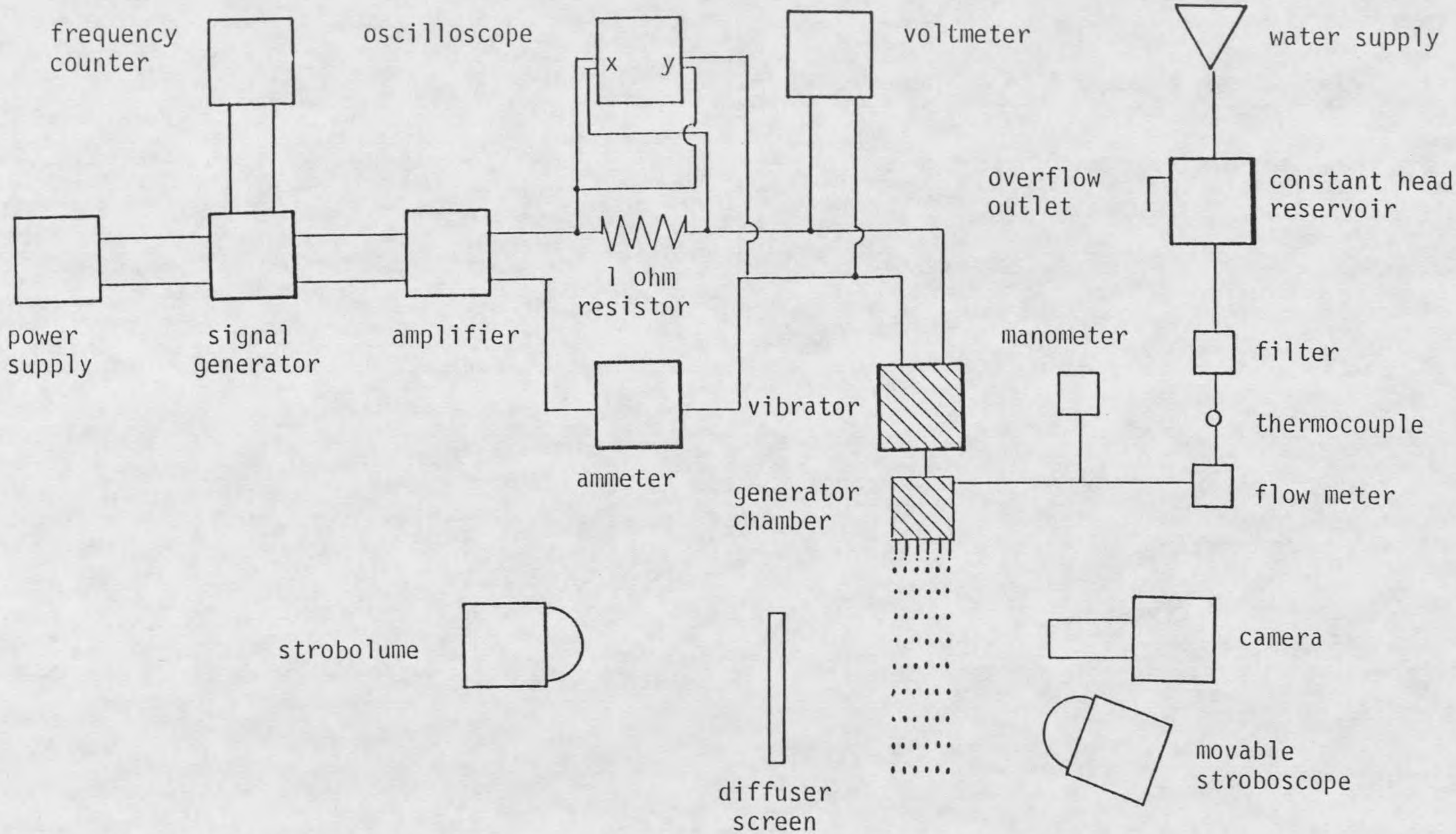

Figure 2: Schematic of Droplet Generator Power and Liquid Delivery Subsystems and Photographic Diagnostics

monitor signal frequency and power consumption are included.

The generator itself (Figure 3) is a cylindrical aluminum chamber (9.5cm i.d.x2.2cm long) fitted on the bottom with an aluminum plate (.3cm thick) drilled to accommodate a set of equally spaced stainless steel capillary tubes. All tubes were carefully machined and polished to ensure that no burrs or other irregularities were present at the ends. Each tube was inspected microscopically to show that all were sized and finished uniformly. The required inside orifice diameter was achieved by epoxying capillary jets (28mm i.d.x.47mm o.d.x23mm long) inside 13mm lengths of .47mm i.d. tubing. These were in turn epoxied into the bottom plate. Nineteen jets were used in all for these studies.

Droplet size instrumentation consisted of a 35mm Lietz-Wetzlar camera body and a Summicron 50mm f/2.0 lens fitted with a 90mm bellows. Image magnification was approximately 2:1. The camera shutter was synchronized with a General Radio 1532A Strobolume (15 μs flash duration) flash source. Photographs were taken with Kodak Plus-X-Pan film (ASA 125) using backlighting. The droplet stream fell between the camera and a 6.4mm thick translucent acrylic sheet through which the flash source was diffused. For visual observation of the stream a General Radio 1531AB Strobotac was used to 'stop' the droplet motion by setting the Strobotac frequency to that of the excitation frequency. In each negative a stainless steel tube of known diameter appeared for size reference, coplanar with the droplet stream. Drops were

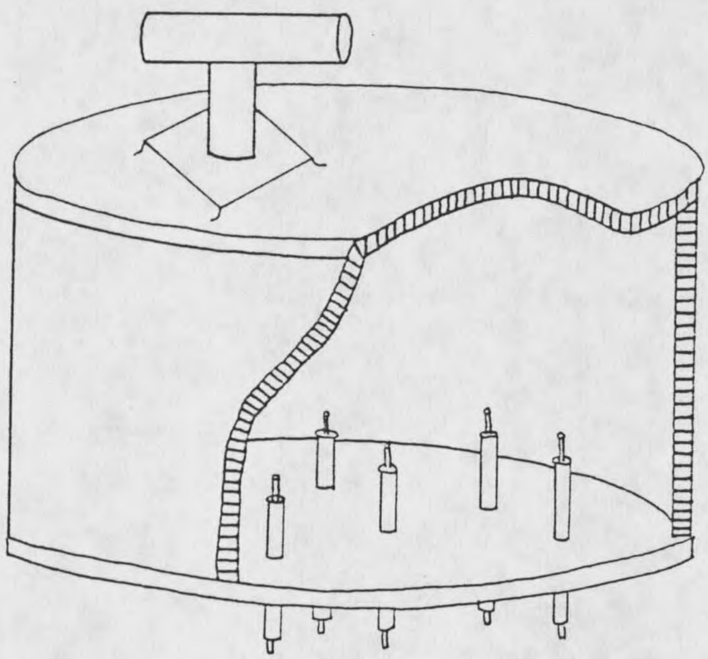

Figure 3: Droplet Generating Chamber

measured from the negatives with a Bausch and Lomb (.7x-3x) stereo measuring microscope.

Experimental Procedure

In characterizing droplet formation, the procedure has been first to determine the operating conditions for the droplet generator during DCHX tests. Next was to devise a data grid prescribing parameter variations away from the DCHX operating conditions. The parameters defining the data grid (jet velocity, vibration frequency and input power) were varied individually 15 to 40 percent above and below a data center case. The data center case corresponds to the optimum droplet operating conditions predicted for the DCHX studies in Chapter III. For example, holding jet velocity and vibration power constant at data center conditions, vibration frequency was varied from 20% below to 20% above its data center. Photographs were taken at each point on the data grid for all jets. Information on droplet formation in the absence of forced vibration was obtained for several jets over a range of velocities. In this manner, droplet uniformity at the data center, and the influence of the above parameters was determined.

Before photographing, tubes were ultrasonically cleaned, the constant head reservoir adjusted and jet velocity determined from mass flow data. Next a predetermined vibration frequency and amplitude were imposed, power consumption data recorded, and droplet motion 'stopped' using the Strobotac. Jet disintegration was then visually inspected to insure the droplet stream fell within the camera's depth of field. A series of three photographs were then taken at this operating condition. At this point one parameter was varied and the process repeated. After development, the negatives were inspected. Of the three negatives taken at each operating condition, only those with the sharpest boundaries, showing a minimum of three droplets per frame were used. Drop measurements came directly from these negatives.

To find actual drop size, developed drop size and magnification ratio had to be known. The magnification ratio is the ratio of developed to actual size of the known diameter stainless steel tube in the negative. Droplet diameter is the average of the major and minor axes dimensions. The given drop size variation is the standard deviation (σ) for all droplets measured (three drops per photograph) for all jets measured (maximum of nineteen) at a specified operating condition.

Results and Discussion

The purpose of this study was twofold. The first concerned showing that a nearly uniform droplet stream was produced by the droplet generator described earlier, at the operating conditions (jet velocities and vibration frequency and power) used in the DCHX studies of Chapter III. It was also important to determine the sensitivity of droplet diameter to changes in vibration frequency and power. Comparison of experimentally determined uniform droplet diameters are made to the theoretical prediction derived earlier.

Since it is proposed that a uniform droplet stream is the most efficient method of heat extraction for the DCHX, the other goal of this particular investigation was to find the degree to which droplets become nonuniform when emanating from a nonvibrating jet. Results are presented as percent standard deviation from the mean, over the range of jet velocities used in the DCHX studies.

Uniform Droplets

The dependence of droplet size and spacing on jet velocity is shown in Figures 4 and 5. The four droplet streams pictured in Figure 4 indicate qualitatively how, at a fixed vibration amplitude and frequency, droplet diameter and spacing increase with increasing jet velocity. Good agreement between equation (2.03) and experimentally determined drop size, plotted as a function of jet velocity, is shown in Figure 5. It is apparent in examining this figure, that although theoretical and experimental values lie within 6% of one another, a systematic error causes all experimental values to lie above their theoretical counterparts. This systematic error may be introduced by uncertainty in calculating the magnification ratio for droplet measurements. Determination of the magnification ratio requires knowing the reference tube's actual size, the microscope's