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Mist Lift Analysis Summary Report

Roger L. Davenport

Solar Energy Research Institute
A Division of Midwest Research Institute

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ROGER L. DAVENPORT

SEPTEMBER 1980

PREPARED UNDER TASK NO. 3451.20

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PREFACE

This report was prepared as part of Task No. 3451.20 within the Ocean Systems Program at SERI. The objective of this task is to study analytically the mist lift process, aiding the decision-making process of the Ocean Systems Program Office. In this report, results from the work performed in FY79 and the first few months of FY80 are summarized. I thank Ben Shelpuk and Dave Johnson for providing leadership and guidance in this work. Lembit Lilleleht and Graham Wallis contributed greatly. Finally, I appreciate the services of the computer centers of Dartmouth College and SERI.

Roger L. Davenport
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Associate Engineer

Approved for:

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SUMMARY

OBJECTIVE

Develop an analytical understanding of the fluid mechanics of the mist lift process to allow decisions to be made about its viability for Ocean Thermal Energy Conversion.

DISCUSSION

This report summarizes the progress made in the study of the mist lift process in FY79 and the beginning months of FY80. Models of a single drop-size mist and a mist composed of many drop sizes have been developed. Results from both models are presented and discussed, as well as directions for further work.

CONCLUSIONS AND RECOMMENDATIONS

Results from the single-group mist flow model indicate that the lift obtained by the mist lift process is sensitive to the amount of temperature flashdown of the water at the inlet. Maximum lift is predicted with a small amount of flashdown; small variations in inlet parameters greatly change the lift height achieved.

Growth of droplets by collision and coalescence is substantial as predicted by the multi-group mist flow model. Because of this growth, the height achieved by the mist flow is reduced substantially from the case of the single-group model. Maximum lift is realized when a large amount of flashdown occurs at the inlet of the lift tube, producing enough vapor to lift the drops while they are still small. As in the case of the single-group model, small changes in inlet parameters greatly change the lift height predicted.

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SECTION 1.0

INTRODUCTION

The mist flow concept is a promising alternative to closed-cycle and other open-cycle ocean thermal energy conversion (OTEC) concepts (Ridgway and Hammond 1978). This concept eliminates the heat exchanger losses of the closed cycle and the huge turbines of the steam-based open cycle in favor of a single direct-contact condenser and a standard hydraulic turbine. The major component of a mist flow OTEC plant is the mist lift tube, which serves to convert the thermal energy of surface seawater into gravitational potential energy, which is transformed into useful work by the hydraulic turbine. The lifting of the water against gravity is accomplished by the vertical flow of a mist of water droplets and low pressure water vapor inside the evacuated lift tube. The mist is generated by injecting warm water into the bottom of the lift tube as fine drops in a superheated condition. The drops evaporate, and the vapor produced expands upwards to the top of the tube, carrying the water drops along by viscous drag. At the top, cold water from deep in the ocean is used to condense the flow of vapor, and the liquid drops are collected.

Although the thermodynamics of the mist lift process are relatively straightforward and support the idea, the fluid mechanics of the flow are not well understood. An understanding of the fluid mechanics of the mist lift process is necessary to assess its viability and sensitivity to variations in the operating parameters. In parallel with the experimental investigations of the mist flow process underway at UCLA (Charwat 1978), the Solar Energy Research Institute (SERI) began an analytical investigation in FY79 to learn more about the fluid mechanics of the process. The analytical work at SERI will also be used to direct, extend, and explain the experimental results.

This report summarizes the progress of the analytical investigations carried out by SERI in FY79 and the first part of FY80. Three models for the mist lift process were developed: two for a mist composed of a single size of drops, and one for a mist consisting of groups of different sized drops. Results from the initial single-group model pointed out the need for improvements and extension of the model that led to the development of the multigroup model. The second single-group model is the degenerate case of a single group of drops in the multigroup model. Section 2.0 discusses the two single-group models and Sec. 3.0 presents the status and results of the multigroup model. Conclusions are given in Sec. 4.0.

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SECTION 2.0

REVIEW OF SINGLE-GROUP MODELS AND RESULTS

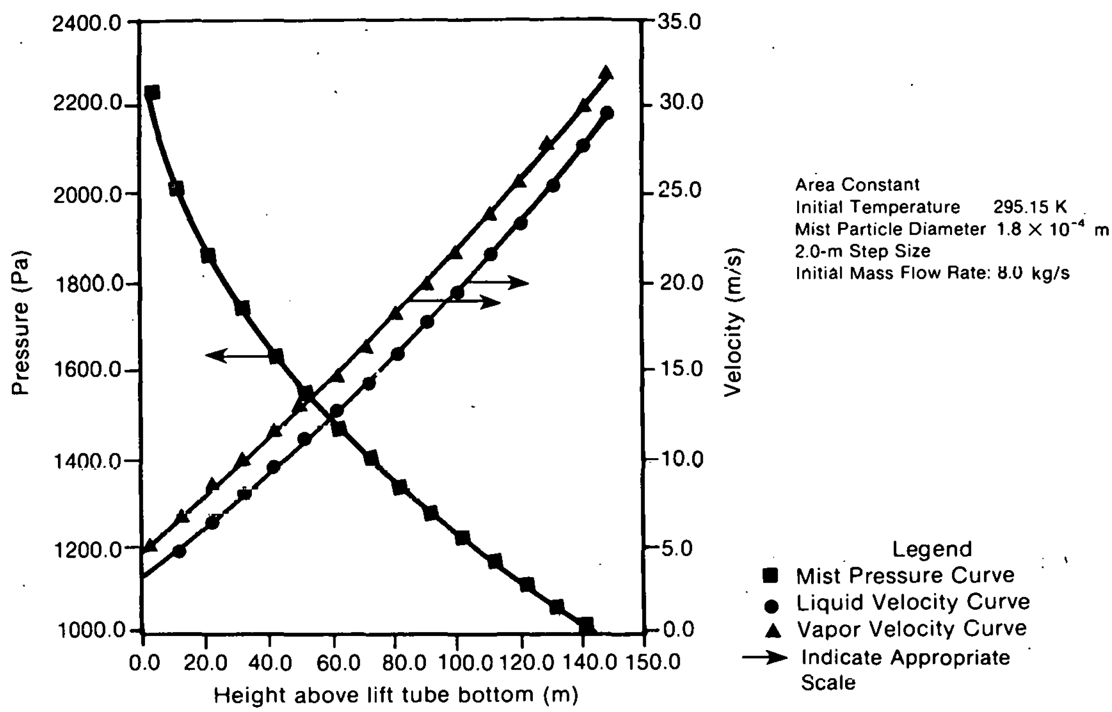
2.1 SINGLE-GROUP MODEL DEVELOPED BY L. LILLELEHT

During the spring and early summer of 1979, SERI began its first analysis of the mist lift process with a one-dimensional steady-state model of the lift tube developed by Lembit Lilleleht of the University of Virginia (Lilleleht 1979). The process considered by this model consists of the injection of warm water into the bottom of the lift tube in small jets, the subsequent break-up of the water jets by Rayleigh instability into droplets, the flashdown of the drops to a mist of drops and vapor, and the flow of this mist up the tube. The major assumptions in this model, in addition to the one-dimensional and steady-state assumptions, are:

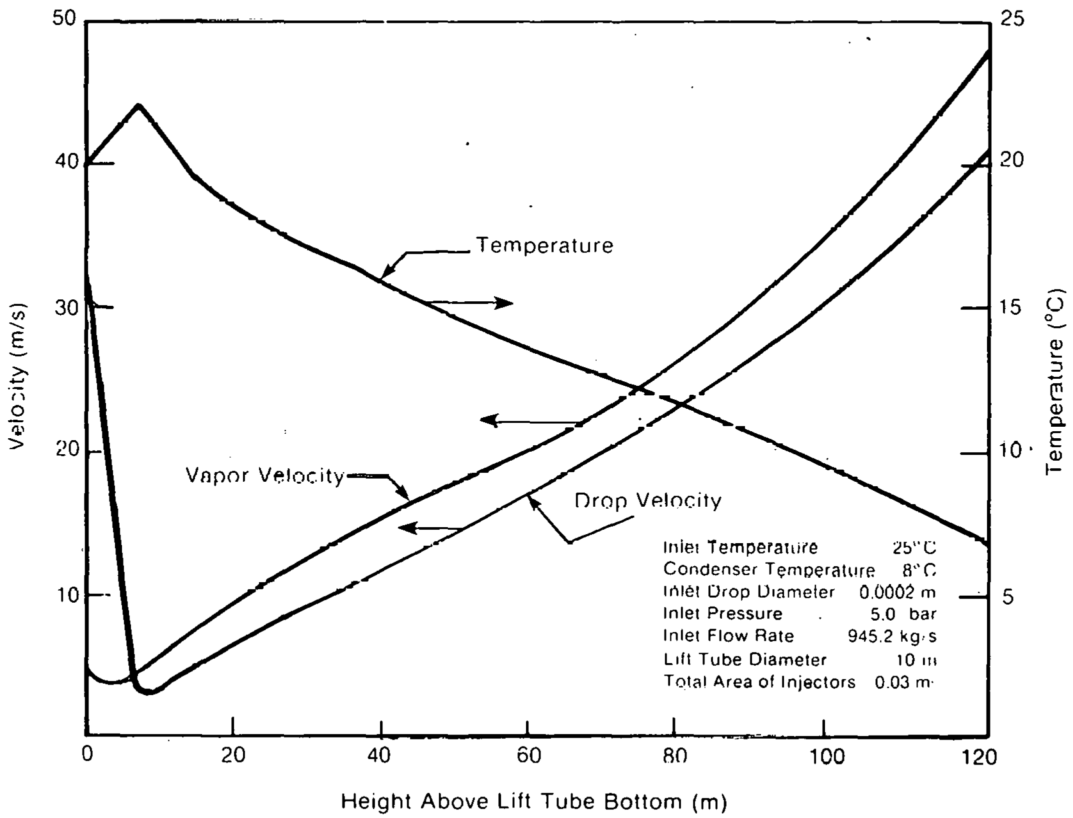
- the drops are of uniform size and spherical;
- thermal equilibrium exists between the drops and the vapor at each location in the lift tube;
- no interactions between drops (collisions or wake effects) are considered;
- the drops are carried at their terminal velocity with respect to the vapor; and
- no wall effects are considered.

The inlet parameters specified are the diameter of the droplets, lift tube shape, mass flow rate of the liquid, water inlet temperature, condenser temperature, and temperature at the bottom of the lift tube. From the temperature at the bottom of the lift tube, the corresponding saturation pressure and the amount of flashdown (temperature change at the inlet) are determined. The number of drops formed at the inlet is calculated from the mass flow rate and droplet size and remains constant. The mass flow rates of vapor and liquid at the inlet are calculated using the overall energy equation for the flow, and from these values the void fraction and velocity of each phase is calculated at the inlet. To advance the solution up the lift tube the pressure at the next step up the tube is first estimated. From this estimate, the equilibrium temperature is determined and values of mass flow rate and velocity are calculated at the new location. These estimated values are used to calculate the expected pressure at the new location using the momentum equation for the overall flow. If the calculated pressure does not agree with the previously estimated pressure (within a specified tolerance), the estimate is revised and the process is repeated. When the values agree, the results are printed and the calculation proceeds to the next step up the lift tube. This process continues until the equilibrium temperature associated with the flow is less than the condenser temperature specified for the run or the height of the lift tube is exceeded. The height at which either condition is achieved is the "lift height" for that run.

The results of the computer program for this model (an example of the output is shown in Fig. 2-1a) verified the basic viability of the concept by predicting lift of droplets by the vapor under OTEC conditions. Lilleleht studied the effects of mist lift tube shape and flow rate on the performance of the mist flow process. Table 2-1 presents some conditions examined in these parametric studies (Lilleleht 1979). The model predicted significant acceleration of the mist in a tube with a constant cross-section (Fig. 2-1a), and considerable change in the performance with slight changes in tube shape. Lilleleht



a. Model Developed by L. Lilleleht



b. Model Developed at Dartmouth College

Figure 2-1. Sample Outputs from Single-Group Models

noted some difficulty in obtaining sufficient lift over a wide range of flow rate and flashdown temperature combinations.

Table 2-1. SAMPLE CONDITIONS FOR PARAMETRIC STUDY BY L. LILLELEHT

Lift Tube Height (m)	Drop Diameter (m)	Inlet Temp. (°C)	Condenser Pressure (Pa)	Lift Tube Bottom Temp. (°C)	Mass Flow Rate (kg/s)	Cross-Sectional Area of Lift Tube[a]				Lift Height (m)	Final Liquid Velocity (m/s)
						A_0	A_1	A_2	A_3		
150.0[b]	0.00018	22.0	880	19.0	8.0	1	0	0	0	150	30.0
150.0	0.00018	22.0	880	19.0	8.0	1	0.0500	0	0	150	2.5
150.0	0.00018	22.0	880	21.0	24.0	1	0.0500	0	0	150	7.1
150.0	0.00018	22.0	880	21.0	16.0	1	0.1830	-2.33×10^{-3}	1.33×10^{-5}	150	1.5
150.0	0.00018	22.0	880	21.0	16.0	1	0.1333	-0.001	6.67×10^{-6}	95	0.7

[a] $A(m^2) = A_0[1 + A_1 z^2 + A_2 z^2 + A_3 z^3]$, where z is the height above the bottom of the lift tube.

[b] Conditions of Fig. 2-1.

In the course of this study the program developed by L. Lilleleht has been modified to model additional effects. The area of the injector orifices has been added as a parameter, permitting direct calculation of the inlet water velocity. A maximum temperature at the bottom of the lift tube is then determined by the flashdown vapor production necessary to fill the lift tube with a flow of liquid and vapor in thermal equilibrium at the velocity of the inlet water. Provision has been made for either calculating this maximum temperature in the program or specifying a flashdown temperature.

The restriction on lift height because of the lift tube height has been removed; calculation is stopped only when the equilibrium temperature falls below the specified condenser temperature. Numerous other small changes have been made to improve the accuracy of correlations contained in the code and the efficiency of the code. Appendix A is a listing of the present code configuration.

The code has been run for a variety of conditions, and these runs are summarized in Table 2-2. General trends are an increase in the lift height with reduced flashdown at the inlet, an increase in the predicted lift for higher flow rates, increased lift for smaller drops, and a strong dependence of the predicted lift height on the shape of the lift tube.

The results from this model are limited, however, by the assumptions used to derive it. In particular, the assumption that droplets are all the same size does not allow for droplet collisions and growth. Also, the treatment of the momentum equation forces the drops to be at their terminal velocity with respect to the vapor at all times, even at the entrance, where significant differences in velocity are expected.

2.2 SINGLE GROUP MODEL DEVELOPED AT DARTMOUTH COLLEGE

In the summer of 1979, Graham Wallis and his colleagues at Dartmouth College developed an analysis of the mist lift process that included a spectrum of drop sizes so that the effects of droplet interactions could be studied. The case of a single drop size can be treated as a degenerate case of that multigroup model (Wallis, Richter,

Table 2-2. SUMMARY OF SERI RESULTS FOR MODEL BY L. LILLELEHT

Date (1979)	Run	Inlet Temp. T_0 (K)	Temp. at Bottom of Lift Tube T_1 (K)	Condenser Temp. T_2 (K)	Drop Diameter (m)	Mass Flow Rate (kg/s)	γ[a]	Lift Tube Cross-Section Area A(z) (m^2)	Lift Height (m)	Final Liquid Velocity (m/s)	Comments
7/12	1-3	300.0	295.0	278.15	0.0002	10.0	—	1.0	150.0	25.0	—
7/13	1	298.15	295.15	278.15	0.00018	16.0	—	1.0	150.0	35.0	—
	2	298.15	295.15	278.15	0.00018	8.0	—	1.0	150.0	22.0	—
	3	298.15	295.15	278.15	0.00018	16.0	—	See Note b	150.0	2.0	—
8/3	1	300.0	290.0	285.00	0.0002	10.0	—	1.0	87.5	21.0	—
	2	300.0	295.0	285.00	0.0002	10.0	—	1.0	125.0	21.0	—
	3	300.0	296.0	285.0	0.0002	10.0	—	1.0	127.5	21.0	—
	4	300.0	295.0	285.0	0.0001	10.0	—	1.0	155.0	23.0	—
8/14	1	300.0	292.6	280.0	0.0002	10.0	—	1.0	192.0	41.0	T_1 calculated[c]
	2	300.0	295.0	280.0	0.0002	10.0	—	1.0	204.0	41.0	T_1 calculated
	3	300.0	293.3	280.0	0.0002	10.0	—	1.0	154.0	60.0	T_1 calculated
8/24-27	1	300.0	294.0	280.0	0.0002	40.0	0.002	1 + 0.05 z	248.0	10.0	T_1 calculated
	2	300.0	293.5	280.0	0.0002	20.0	—	1 + 0.05 z	200.0	6.0	T_1 calculated
	3	300.0	294.2	280.0	0.0002	60.0	—	1 + 0.05 z	276.0	15.0	T_1 calculated
	4	300.0	294.1	280.0	0.0001	40.0	—	1 + 0.05 z	286.0	10.0	T_1 calculated
	5	300.0	293.5	280.0	0.0004	40.0	—	1 + 0.05 z	184.0	10.0	T_1 calculated
	6	290.0	286.1	280.0	0.0002	40.0	—	1 + 0.05 z	78.0	15.0	T_1 calculated
	7	295.0	290.2	280.0	0.0002	40.0	—	1 + 0.05 z	152.0	13.0	T_1 calculated
	8	300.0	294.1	280.0	0.0002	40.0	—	1 + 0.01 z	300.0	35.0	T_1 calculated
	9	300.0	293.4	280.0	0.0002	40.0	—	1 + 0.04 z	256.0	12.0	T_1 calculated
	10	300.0	293.8	280.0	0.0002	40.0	—	1 + 0.1 z	210.0	6.0	T_1 calculated
	11	300.0	286.5	280.0	0.0010	20.0	—		56.0	8.0	T_1 calculated
8/31	1	300.0	293.9	280.0	0.0002	40.0	0.002	b	192.0	2.0	T_1 calculated
	2-4	298.15	293.75	283.15	0.0002	56.28	0.0027	1 + 0.053 z	160.0	13.0	T_1 calculated
	5	298.15	292.33	183.15	0.0002	56.28	0.0027	1 + 0.053 z	158.0	13.0	T_1 calculated
	6	298.15	290.0	283.15	0.0002	56.28	0.0027	1 + 0.053 z	160.0	13.0	T_1 calculated

[a] $\gamma = \dfrac{\text{Injector Hole Area}}{\text{Lift Tube Cross-Sectional Area}}$

[b] $A(z) = 1.0 + (0.183)z - (0.00233)z^2 + (1.33 \times 10^{-5})z^3$.

[c] At this point, parameter γ was added to the program for all subsequent runs.

Bharathan 1979). This subsection discusses this single-group model; the multigroup model is discussed in Section 3.

The single-group analysis developed by Wallis is also one dimensional and assumes steady-state conditions but includes many improvements over the Lilleleht model. An improved treatment of flashdown is formulated by the application of Bernoulli's equation to the region of the injectors; thus, the flashdown temperature and pressure are determined by the inlet flow rate and the pressure upstream of the injectors. Also, a more complete treatment of the momentum equation is included, allowing calculation of the acceleration of the droplets with respect to the vapor. This acceleration of the droplets relative to the vapor is easily seen in the plot of the output from a typical run (Fig. 2-1b).

The following algorithm is employed to solve the governing equations in this model. Input parameters are the drop size, the liquid mass flow rate, the pressure upstream of the injector, the total area of injector holes, the inlet temperature, the condenser temperature, and the geometric shape of the lift tube. By using the inlet parameters in Bernoulli's equation, the equilibrium pressure just inside the lift tube is calculated, which determines the equilibrium temperature and amount of flashdown. As in Lilleleht's model, the drops are assumed to form and their flashdown to equilibrium is assumed to occur within the first vertical step. Once the inlet conditions are established, a step size up the tube is chosen and the droplet momentum equation is employed to find the change in drop velocities over that step up the tube; a forward finite difference expression is used to approximate the derivative of velocity with respect to height. Then the overall momentum, mass, and energy conservation equations for the flow are solved simultaneously to yield the changes in steam quality, pressure, and vapor velocity for the step to the new location. Finally, the drop velocity, quality, pressure, and vapor velocity variables are updated to the new location, the change in droplet mass resulting from evaporation is calculated, and output is generated. This process is repeated until the equilibrium temperature at a point becomes less than the specified condenser temperature or until the droplet velocity is less than zero. If calculation stops because of the bulk temperature reaching the temperature of the condenser, the drops may have considerable kinetic energy that could lead to further lift in a suitably designed "coasting" section of lift tube. Such a coasting section would be designed to recover the kinetic energy of the flow by allowing it to follow a ballistic trajectory without temperature change. The occurrence of negative drop velocities implies "rainout," because the drops are no longer lifted by the vapor and begin to fall back down the lift tube. In either case, the lift height is defined as the height at which calculation stops.

The predictions of this model are quite sensitive to the inlet conditions, especially the mass flow rate and pressure upstream of the injector. In Fig. 2-2 an example of the results obtained at Dartmouth College using this model (Wallis, Richter, Bharathan 1979) are plotted as curves of predicted lift height versus mass flow rate at selected input pressures. For a given set of conditions, variation of the flow rate by as little as 1% leads to large changes in the predicted lift height if possible recovery of kinetic energy by a coast phase is not considered.

In the low flow rate region of the curves in Fig. 2-2, the pressure calculated from Bernoulli's equation for the bottom of the lift tube is relatively high, meaning that little flashdown occurs, and thus the vapor velocity is small. The drops are injected into this almost stagnant vapor and are slowed by drag forces and gravity until they stop, so that rainout occurs after only a few meters. The large discontinuity at the left end of each curve corresponds to the flow rate at which just enough vapor is generated by flashdown

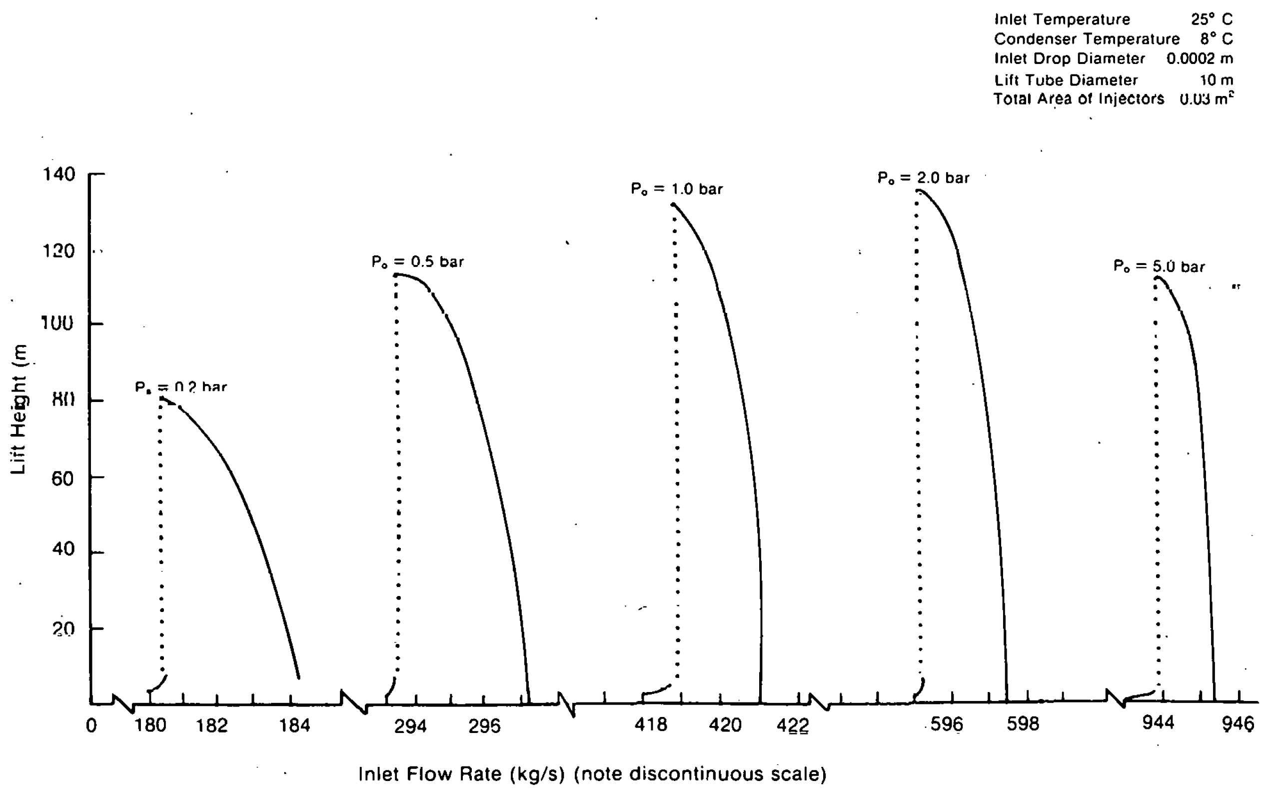


Figure 2-2. Dependence of Lift on Flow Rate Predicted by Dartmouth Single-Group Model for Various Inlet Pressures (Dotted Lines Indicate Discontinuity in Lift Height, where Rainout Ceases)

to accelerate the drops up the tube just before they stop because of the force of gravity. This condition leads to a maximum lift height. As the flow rate is increased, the predicted pressure at the bottom of the lift tube decreases, which leads to increased flashdown and higher vapor velocities at the inlet. Since the temperature drop is greater at the entrance, the condenser temperature is reached sooner, and the lift height predicted is less. However, the velocities of the vapor and droplets are not zero when the temperature of the condenser is reached, and so kinetic energy is available for recovery by coasting. The high-flow-rate cutoff of each curve corresponds to the flow rate at which the flashdown temperature is calculated to be the temperature of the condenser immediately upon entrance, therefore, the calculation is terminated. Again, inclusion of a coast section would increase the lift height above the predictions. Table 2-3 summarizes the results of the Dartmouth College studies and also subsequent investigations.

Table 2-3. SUMMARY OF RESULTS FOR MODEL DEVELOPED AT DARTMOUTH COLLEGE

Location of Runs	Inlet Temp. T_0 (°C)	Condenser Temp. T_2 (°C)	Inlet Pressure (bar)	Mass Flow Rate (kg/s)	Total Area of Injector Orifices (m^2)	Area of Lift Tube (m^2)	Drop Diameter (m)	Lift Height h_0 (m)	Final Liquid Velocity v (m/s)	Lift Height with Coast Phase[a] h (m)	Comments
Dartmouth College[b]	25	8	0.2	181-184	0.03	78.54	0.0002	0-78.0	—	—	See Fig. 2-2
	25	8	0.5	293-296	0.03	78.54	0.0002	0-112.0	—	—	
	25	8	1.0	418-421	0.03	78.54	0.0002	0-131.0	—	—	
	25	8	2.0	595-598	0.03	78.54	0.0002	0-134.0	—	—	
	25	8	5.0	945-947	0.03	78.54	0.0002	0-110.0	—	—	
SERI	25	8	5.0	946.2	0.03	78.54	0.0001	36.0	39.7	116.4	See Fig. 2-3
	25	8	5.0	946.2	0.03	78.54	0.00015	40.8	37.8	113.8	
	25	8	5.0	946.2	0.03	78.54	0.0002	45.4	35.8	110.9	
	25	8	5.0	946.2	0.03	78.54	0.0004	59.2	28.5	100.7	
	25	8	5.0	946.2	0.03	78.54	0.0008	70.0	17.1	84.9	
	25	8	5.0	946.2	0.03	78.54	0.001	70.6	12.5	78.5	
	25	8	5.0	946.2	0.03	78.54	0.002	57.4	0	57.4	Rainout
	25	8	5.0	946.2	0.03	78.54	0.005	52.6	0	52.6	Rainout
	28	8	5.0	946.2	0.03	78.54	0.01	51.8	0	51.8	Rainout
SERI	25	8	0.1	1120-1266	0.30	78.54	0.0002	0-85.8	0-41.5	0.6-169.6	See Fig. 3-5
	25	8	0.2	1750-1840	0.30	78.54	0.0002	0-39.2	0-47.0	1.2-149.8	

[a] $h = h_0 + \frac{v^2}{2g}$; $g = 9.8066\ m/s^2$.

[b] Duplicated at SERI after transferring code to SERI's computer.

Figure 2-3 demonstrates the possible improvement in lift height made available by allowing a coast region at the condenser temperature. Figure 2-3 is a plot of predicted lift height versus flow rate for two values of inlet pressure, both with and without consideration of a coast region. The extrapolation for the coast was made by considering a ballistic trajectory for the drops from the point at which the calculation originally stopped. Although the low-flow rate cutoff remains unchanged, inclusion of a coast section greatly increases the possible lift for all flow rates above this cutoff. It must be noted, however, that to obtain these results the shape of the lift tube was optimized for each flow rate and that the optimum shape for one flow rate will not be optimum for another.

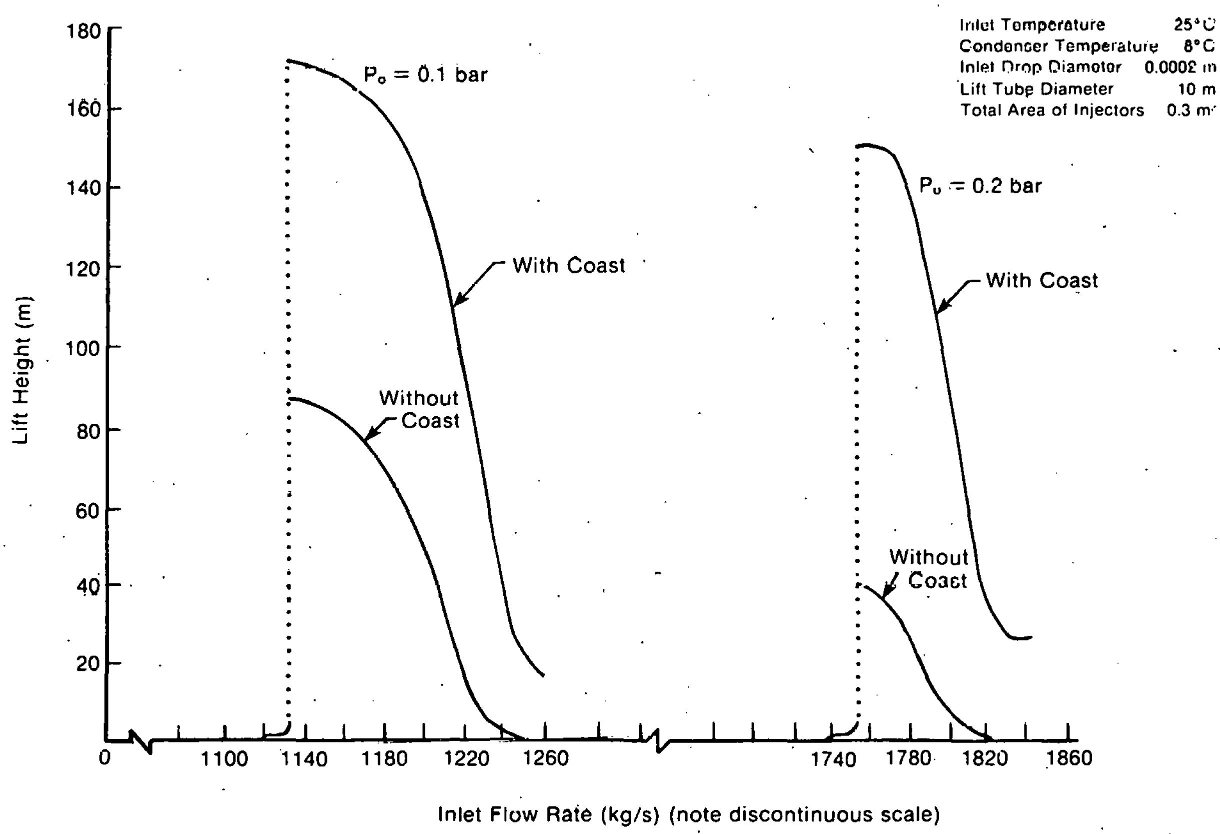


Figure 2-3. Dependence of Lift on Flow Rate With and Without a Coast Phase at the Condenser Inlet (Dotted Lines Indicate Discontinuity in Lift Height Where Rainout Ceases)

SECTION 3.0

MULTIGROUP MODEL

3.1 DESCRIPTION

Studies of clouds and of small droplets entrained in flows indicate that droplet growth by coalescence will be significant in the conditions envisioned for the mist flow OTEC process (Abbott 1977). A single drop-size model cannot include this effect; therefore, a multigroup model was developed that considers a spectrum of drop sizes (Wallis, Richter, Bharathan 1979). The single group model discussed in Sec. 2.2 is the degenerate case of this model.

The drop spectrum is constructed by apportioning the drops into a series of discrete drop-sized groups. Each group consists of drops whose masses are chosen as an integral multiple of the mass of the drops in the smallest group; thus the mass of a drop in group j is taken to be (jm_1) where m_1 is the mass of a drop in group 1, the smallest group. The spectrum consists of fifty contiguous drop sizes, which gives a range of drop diameters up to about four times the diameter of the smallest drops.

A geometric collision cross section based on the diameters of the interacting drops is employed to calculate the number of collisions between different groups of drops, and all collisions are assumed to result in coalescence. Since the drop spectrum is constructed with equal mass increments between groups, drops from groups i and j coalesce to form a drop in group (i + j), making the bookkeeping involved with droplet interactions simple.

The algorithm is similar to the algorithm for the single group model described in Sec. 2.2. Instead of one specific drop size, the smallest drop mass and the initial number of drops in each group of the spectrum are input. All other inputs are the same as for the single group model. At each step up the lift tube, calculations are made of the interactions between the fifty groups of droplets to determine the evolution of the drop size spectrum owing to collisions. For each group of drops, the droplet momentum equation is applied to obtain the average velocity of that group. Finally, solution of the overall conservation equations yields the temperature, quality, and vapor velocity at each step. Thus, the flow properties and the evolution in size and velocity of the drop spectrum are obtained as the mist proceeds up the lift tube. The calculation is terminated when the equilibrium temperature becomes that specified for the condenser, or any group of drops acquires a zero velocity, implying rainout.

3.2 IMPROVEMENTS MADE TO THE MULTIGROUP MODEL

When the multigroup model developed at Dartmouth was run for OTEC conditions, the original 50-group spectrum soon filled with drops, and drops were "lost" beyond the end of the spectrum. To eliminate this problem, an algorithm was developed to "squish" the spectrum when it grew too large. Conserving mass and momentum, the algorithm combines the 50-drop spectrum by pairs into the smallest 25 drop sizes of a 50-drop-size spectrum with a smallest drop mass twice that of the original smallest drop. Calculation then proceeds with the new spectrum of 50 drop sizes. The criterion chosen for this process was to squish whenever the number of groups each containing more than 1% of the total mass flow exceeded a value of eight. This criterion led to consistent squishing of the spectrum without large losses at the end of the spectrum and without overly limiting its extent.

Once the program was modified by the addition of the squishing routine, the drop spectrum could be followed as the drops became much larger. With larger drops, Abbott's results (1977) indicate a reduction in the coalescence efficiency resulting from the onset of phenomena such as bouncing and disruption. Also, the size of a drop is ultimately limited by the balance of the drop's surface tension and fluid pressures from the flow. A coalescence efficiency model was developed, based on Abbott's results, for drops falling through air at their terminal velocities (summarized as a plot of probability contours for different interactions on axes of drop sizes in Fig. 3-1). The probability of coalescence was digitized from the contours of Fig. 3-1 for the range of drop sizes encountered in the mist flow and entered as a subroutine to the multigroup mist lift model. Pairs of drops not coalescing were assumed to separate without satellite drops or exchange of mass. An upper limit on drop size was also coded into the program so that drops could not combine to create a drop larger than the limiting drop size.

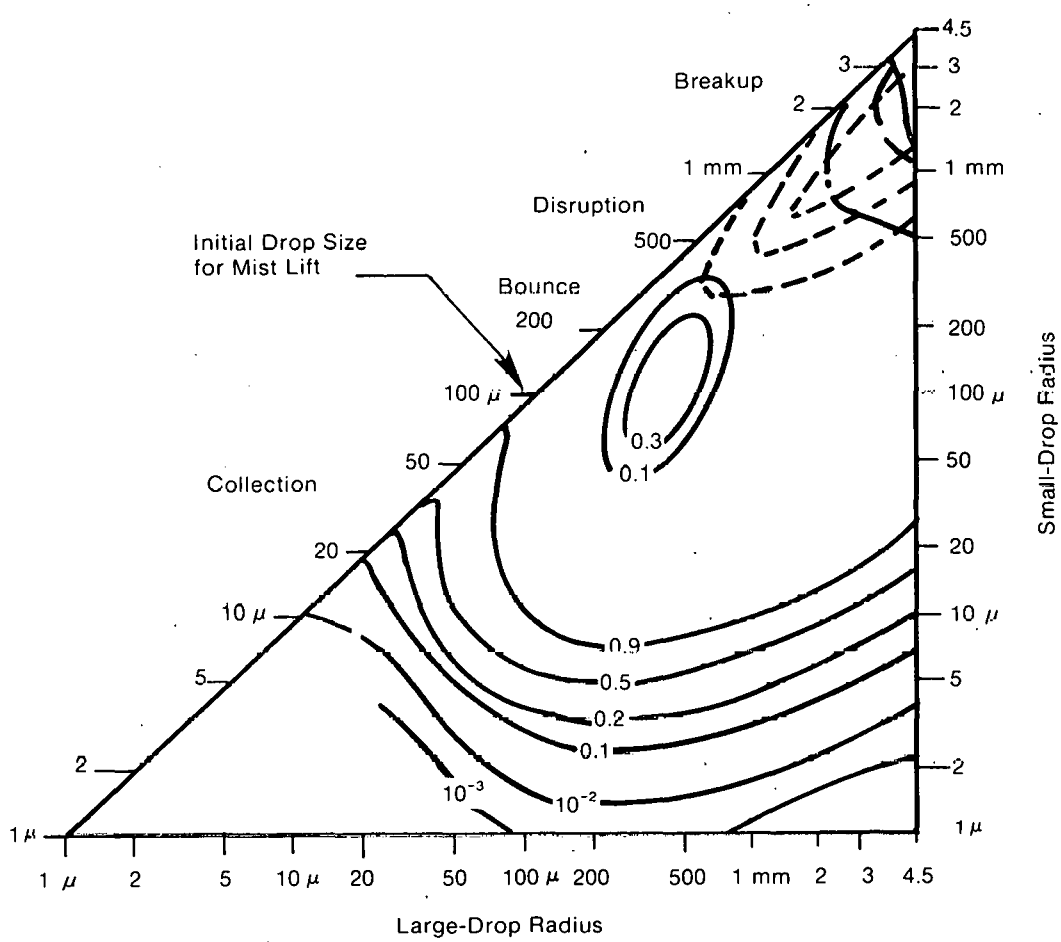


Figure 3-1. Probability Contours for Drop Interactions of Drops Falling at Terminal Velocities at Atmospheric Conditions (From Abbott 1977)

Several other modifications have been made to the computer program to increase the accuracy of the computational procedure. The step size for progressing up the lift tube, originally constant, is now reduced when the velocity of any group of drops is small. This eliminates a problem at low velocities where the step size is originally chosen to be larger than the ballistic height to which drops could rise, exceeding the limits of the numerical approximation of the momentum equation. The step size is also reduced if the change in velocity between steps is more than 20%. This eliminates occasions when a large drag force owing to high slip at the inlet is allowed to act over too large a step causing unrealistic changes in velocity. Finally, the step size is reduced if more drops are removed from a group than existed in that group at the end of the previous step. This change ensures that mass is conserved and that no groups have a negative number of drops. The present version of the program, including these modifications and additions, is listed in Appendix B.

3.3 COMPARISON OF SINGLE-GROUP AND MULTIGROUP MODELS

3.3.1 Individual Results

With the improvements described in Sec. 3.2 included in the multigroup model, and using the distribution of drop sizes measured by Charwat (1978), results such as those plotted in Fig. 3-2 are obtained. The two downward sloping curves are the velocities of the smallest and largest drops in the drop size spectrum as the spectrum develops up the length of the lift tube. The other curve is the plot of vapor velocity versus distance up the tube. The points at which squishing of the spectrum occurred are indicated by the downward-pointing arrows.

Figure 3-3 shows the single-group model results for the conditions of Fig. 3-2 with a drop diameter of 0.0002 m. The smallest drops in Fig. 3-2 behave much like those of the single group model at the entrance, but the growth of the drops by coalescence prevents them from being supported by the vapor and they eventually rain out.

Figure 3-4 is a summary plot of the single-group drop velocity profiles under the conditions of Fig. 3-2 for a range of drop diameters from 0.0001-0.01 m. Also plotted in Fig. 3-4 is a ballistic trajectory, which represents the limit of no lift at all. The shape of the velocity curves of Fig. 3-2 are indicative of a spectrum with drop diameters initially between 0.0002 m and 0.0004 m, growing as they proceed up the lift tube to a spectrum of drop diameters between 0.001 m and 0.005 m. The lift predicted by the multigroup model is about 30 m higher than a ballistic trajectory for these conditions.

Table 3-1 presents results for some of the conditions investigated with the multigroup model to date.

3.3.2 Mass Flow Rate-Inlet Pressure Sensitivity

The apparent sensitivity of the mist lift process to mass flow rate and inlet pressure noted in the single-group model appears also in the multigroup model. Plotted in Fig. 3-5 are the predictions of the single and multigroup models for the range of conditions used in Fig. 2-2. Figure 3-6 contains the predictions of the two models for the conditions of Fig. 2-3.

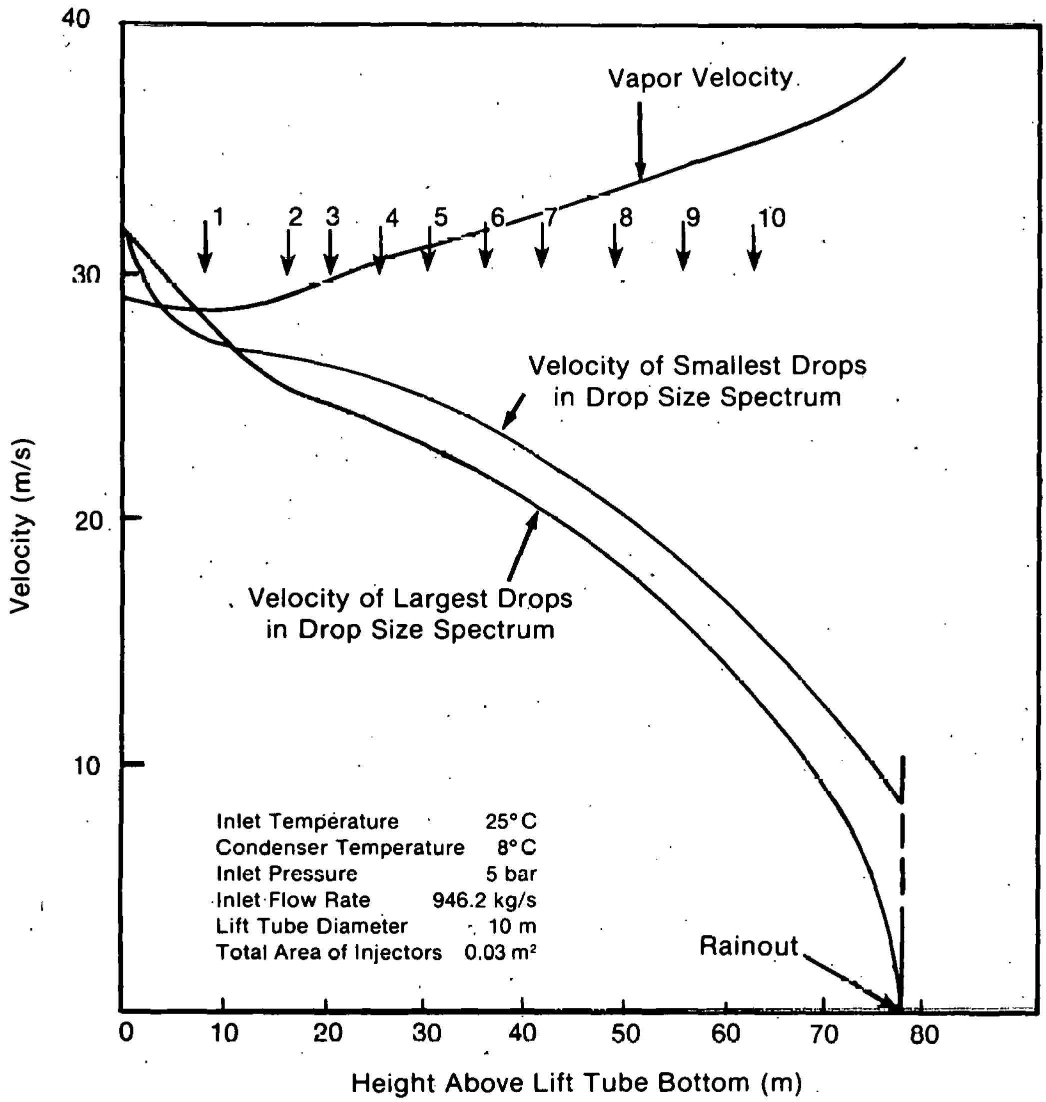


Figure 3-2. Sample Results from Multigroup Model with Squishing and Coalescence Efficiency Effect (Arrows Indicate Locations at which Squishing Occurred)

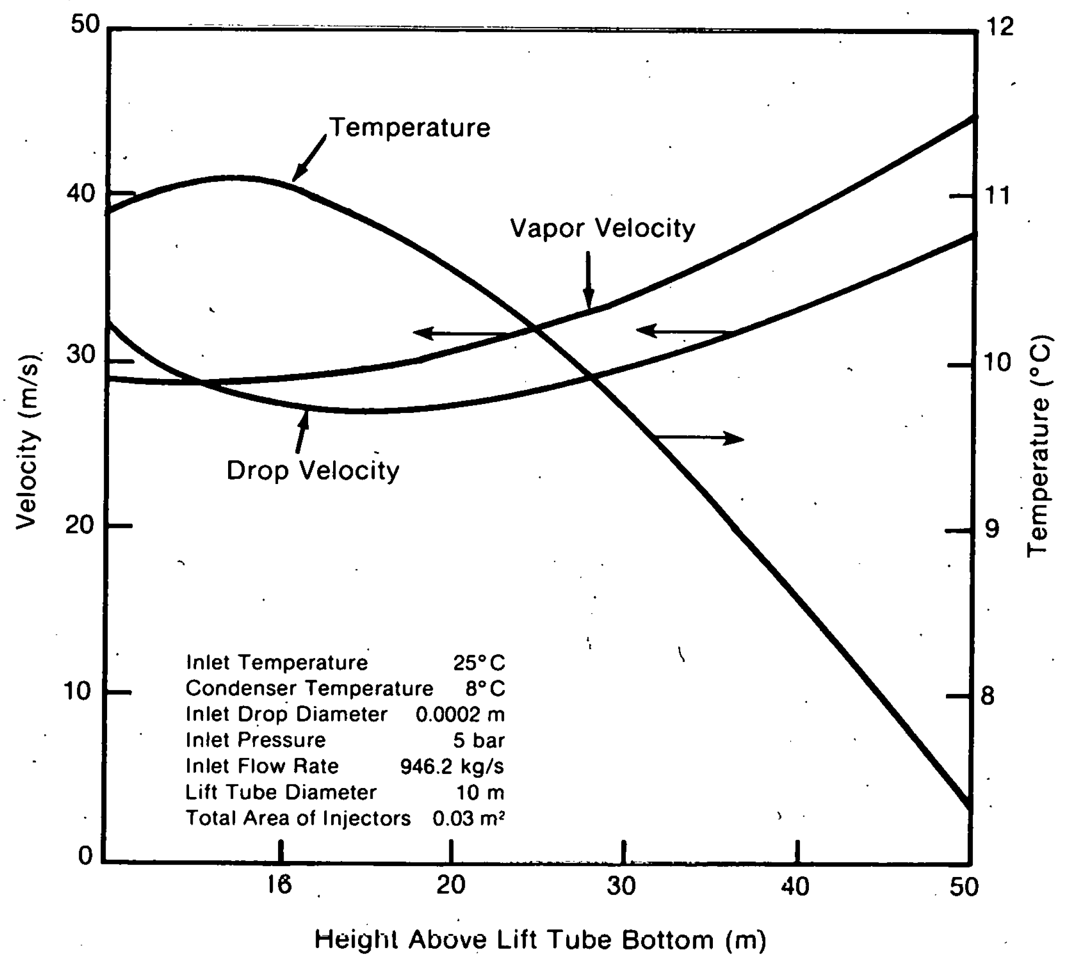


Figure 3-3. Single-Group Model Result for the Conditions of Fig. 3-2

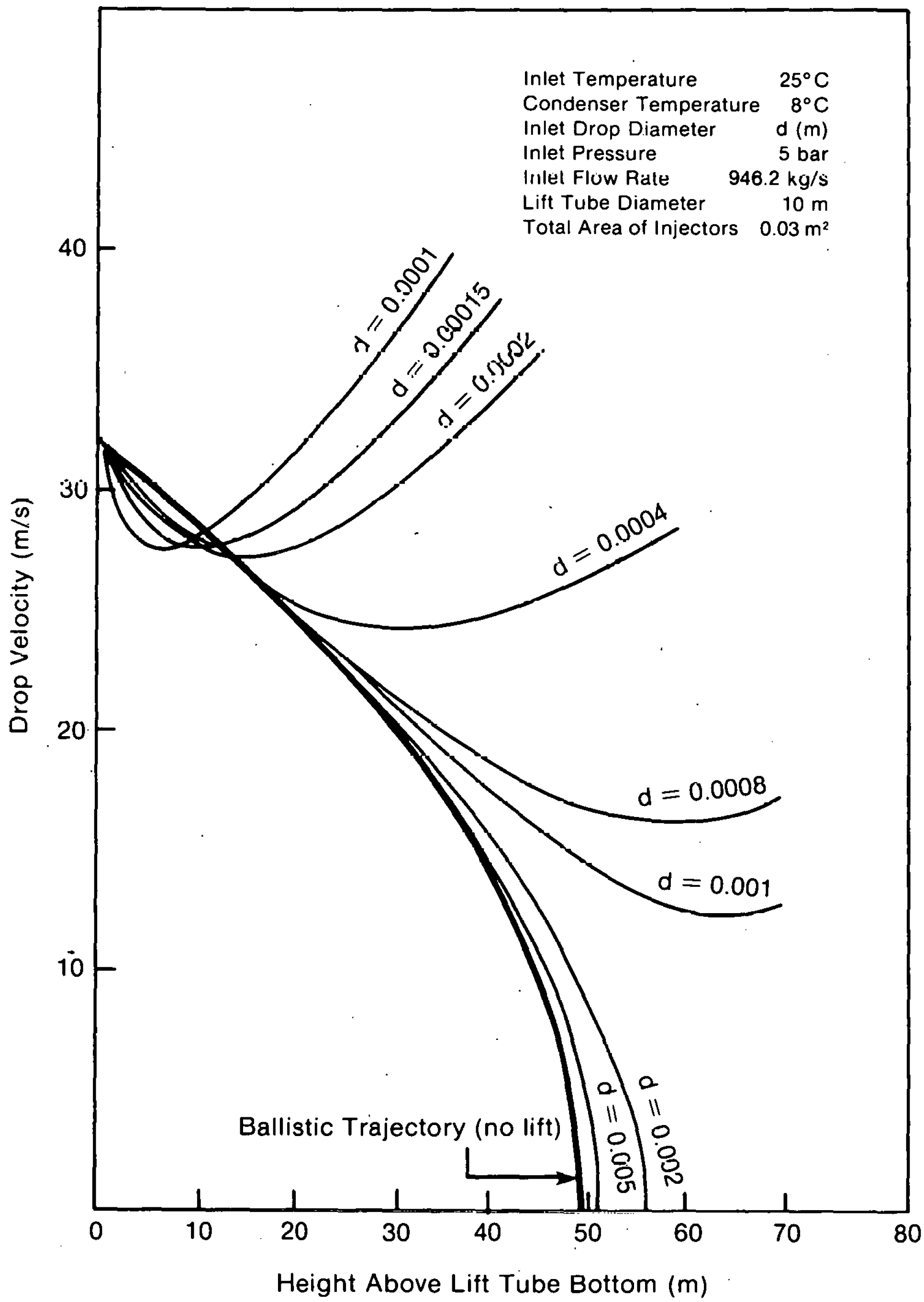


Figure 3-4. Effect of Drop Size on Predicted Performance of Single-Group Model for the Conditions of Fig. 3-2

Table 3-1. MULTIGROUP MODEL RESULTS

Date	Run	Inlet Temp. T_0 (°C)	Condenser Temp. T_2 (°C)	Inlet Pressure P_o (bar)	Mass Flow Rate W (kg/s)	Area of Injector A_0 (m^2)	Area of Lift Tube A (m^2)	Lift Height (m)	Final Liquid Vel. Minimum (m/s)	Final Liquid Vel. Maximum (m/s)	Comments
12/10/79	1-8	25	8	5.0	944-946.4	0.03	78.54	2.22-50.93	—	—	See Fig. 3-5
12/11/79	23-26	25	8	0.2	182-184.5	0.03	78.54	0.67- 4.78	—	—	See Fig. 3-5
	17-22	25	8	0.5	294-296.5	0.03	78.54	0.67-11.08	—	—	
	10-16	25	8	1.0	410-421.4			1.48-25.35	—	—	
	1-9	25	8	2.0	595-598	0.03	78.54	0.29-40.73			
12/14/79	1	25	8	5.0	946.2	0.03	78.54	77.60	0	0	Coalescence efficiency model
	2	25	8	5.0	946.2	0.03	78.54	76.48	0	0	Coalescence efficiency = 1
12/10 to 1/3/79	1	25	8	5.0	946.2	0.03	78.54	78.64	0	0	
	2	25	8	5.0	946.2	0.03	78.54	78.64	0	0	Changes in calculation of Δz (velocity)
	3	25	8	5.0	946.2	0.03	78.54	77.92	0	0	
1/18/80	1-10	25	8	0.1	1135-1260	0.30	78.54	0.14-20.10	—	—	See Fig. 3-5
1/21/80	1-8	25	8	0.2	1750-1820	0.03	78.54	1.88-34.98	—	—	

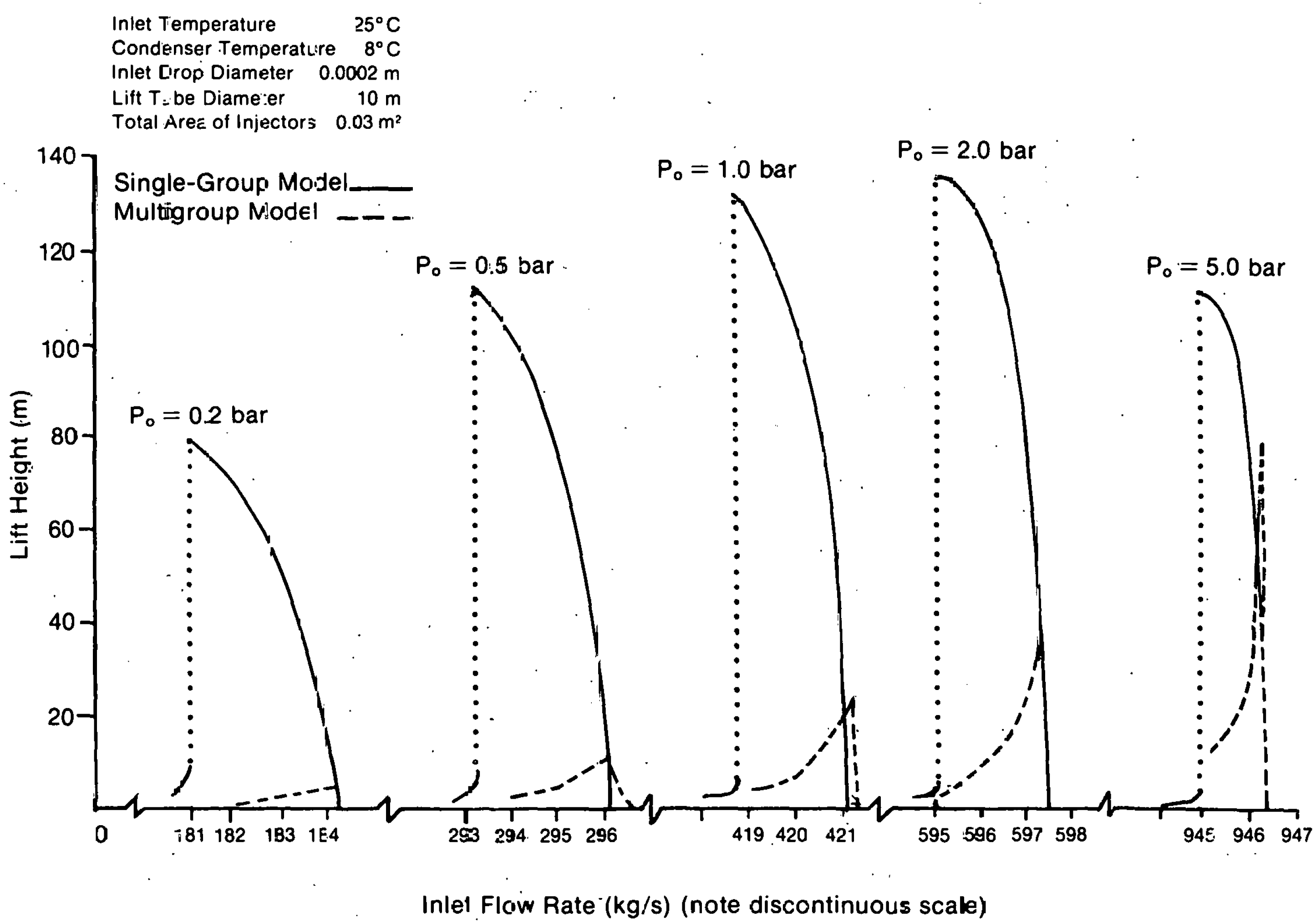


Figure 3-5. Comparison of Mist Lift Predictions of Single-Group and Multigroup Models for the Conditions of Fig. 2-2 (Dotted Lines Indicate Discontinuity in Lift Height Predicted by Single-Group Model where Rainout Ceases.)

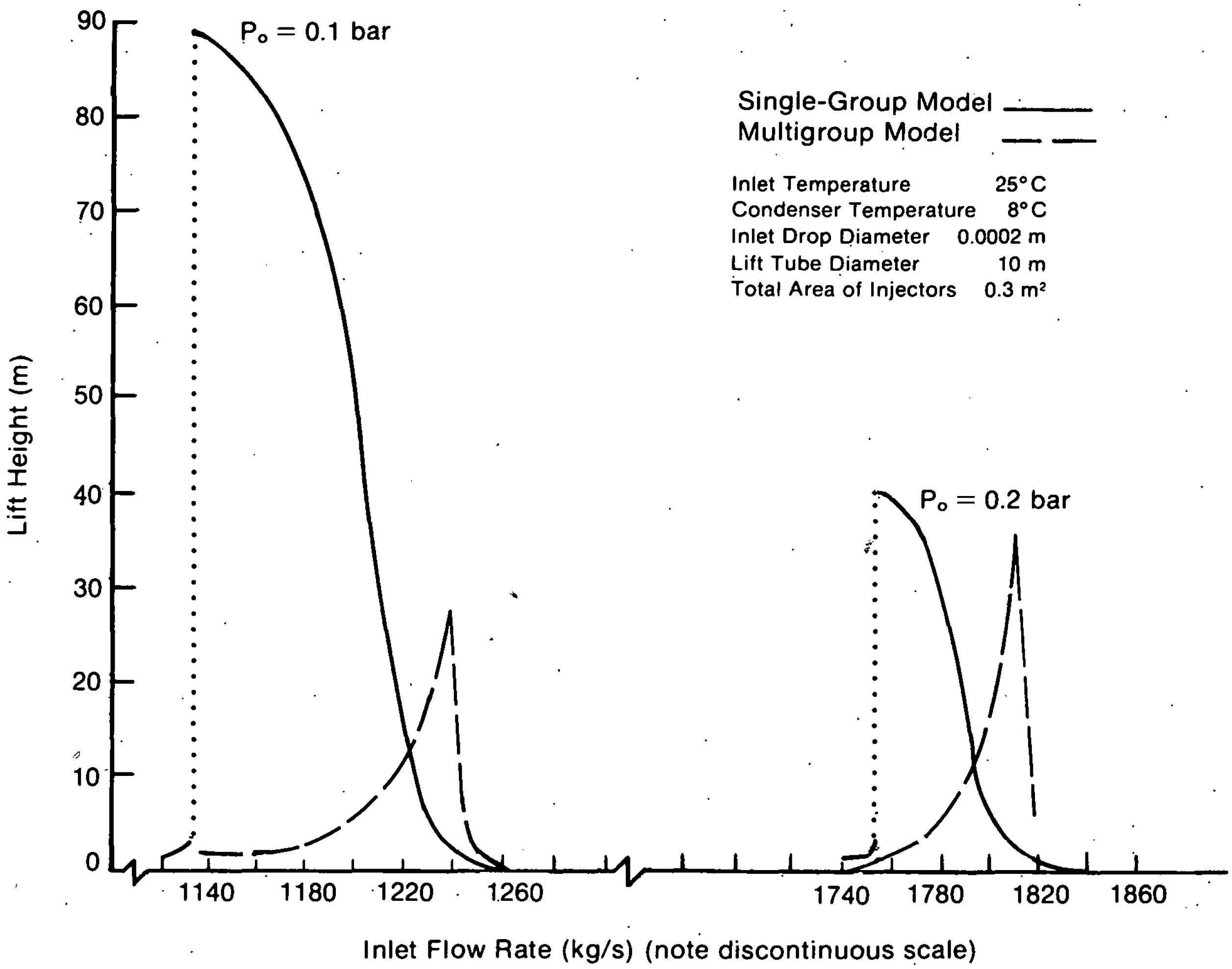


Figure 3-6. Comparison of Mist Lift Predictions of Single-Group and Multigroup Models for the Conditions of Fig. 2-3 (Dotted Lines Indicate Discontinuity in Lift Height Predicted by Single-Group Model where Rainout Ceases)

For the multigroup model, the growth of the drops in the spectrum causes the drops to rain out unless there is enough flashdown at the bottom of the left tube to generate a substantial amount of vapor to sustain the drops as they grow. The predicted lift for the low flow rates, where the flashdown is small, is therefore much less for the multigroup model than for the single group model. As the flow rate is increased, the amount of flashdown and hence the amount of vapor generated increases. Thus, the vapor velocity increases, and the drops are lifted more by the vapor before raining out. This process yields an increasing lift height before rainout with increasing flow rate (see Figs. 3-5 and 3-6) to a point at which the flashdown temperature becomes nearly equal to the condenser temperature. At this point, the multigroup model predicts the greatest lift height. Beyond the point of maximum predicted lift height, the predicted behavior is similar to the behavior of the results of the single group model. The predicted lift decreases because the temperature of the condenser is soon reached; however, the drops still have kinetic energy. The lift increases with inlet pressure because injection velocities increase with inlet pressure, and thus the ballistic height is increased.

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SECTION 4.0

CONCLUSIONS AND RECOMMENDATIONS

4.1 CONCLUSIONS FROM SINGLE-GROUP MODEL RESULTS

The most significant conclusion from the single-group model is that the predicted range of inlet pressure/flow rate combinations is rather narrow under which the mist flow will operate. Within this range, the possible height of the lift may be greatly increased by the inclusion of a coast section, which would allow a wider range of operation for a given height of lift tube. The current injector design causes the drops to be injected into an almost stagnant layer of vapor, resulting in large friction losses and a sharp low-flow rate cutoff in the allowable pressure/flow rate operational envelope. An injector designed to allow the drops to be introduced at nearly the velocity of the vapor over a wide range of flow rates would alleviate this problem. Another conclusion is that the shape of the lift tube has a strong influence on the performance of the mist lift.

4.2 CONCLUSIONS FROM MULTIGROUP MODEL RESULTS

The results of the multigroup model indicate that the growth of droplets by collision and coalescence will be significant. The multigroup model also shows sensitivity to flow rate and pressure. The growth of the drops in the spectrum reduces the lift height achieved and the range of operation without rainout. Maximum lift is achieved when a large amount of flashdown occurs at the inlet, producing sufficient vapor to lift the drops while they are still small. This suggests that large flashdowns at the inlet and a lift tube shaped to provide a coast phase for the drops after they have grown large is the preferable design for mist lift columns.

4.3 UNANSWERED QUESTIONS

The following questions remain unanswered:

- Have all of the important physical effects been considered in the injector calculation? Is there some mechanism that could be used to force the flow to correspond to the pressure/flow rate characteristic that has been noted?
- The coalescence efficiency used in the analysis is based on drops falling at terminal velocities in air at atmospheric pressure. Are the results applicable to drops falling in their own vapor at low pressures and not at terminal speeds? If not, what modifications to the coalescence efficiency model need to be made?
- Depending upon the shape of the lift tube, might drop deposition on the walls be a substantial problem?
- Transient response of the flow to changes in inlet parameters has not yet been assessed. If the response time of the mist tube to perturbations is slow, the control problem might be greatly alleviated. Also, do perturbations to the flow cause oscillations that would increase in time and cause the flow to become unstable?

- Are there alternatives to the present design that would make the mist lift less sensitive to inlet parameters? A different injector might be designed that would avoid the problems of injecting the drops into a nearly stagnant layer of vapor. For example, vapor might be produced separately by staged evaporation and then introduced with the drops at the bottom of the lift tube.
- What shape of the lift tube will give maximum height of lift or range of operation?
- How will the inclusion of a condenser at the top of the lift tube affect the behavior of the mist flow? Will it act as a sink for the mist impinging on it, or will it greatly affect the entire flow of the mist?
- Under what conditions might large-scale instabilities arise, such as annular flow of the vapor where the vapor would flow along walls of the lift tube, leaving the drops in the center of the tube unsupported?

4.4 FUTURE WORK

With the questions of Sec. 4.3 in mind, the work planned for the rest of FY80 includes:

- A search for further information on the collision of drops in low-pressure vapor.
- Continued improvement and evaluation of the multigroup computer code. The effect of varying the parameters of the collision efficiency model will be investigated to determine the sensitivity of the results to the parameters of the model.
- Development of a transient one-dimensional model for the mist flow process and study of the transient response of the system to changes in the inlet conditions. Start-up of the mist lift system will be investigated.
- Investigation of alternatives to the current design of the injector. Such alternatives include staged evaporation to produce vapor that will be introduced into the lift tube, and choke flow nozzles that would inject the water into the lift tube and would be insensitive to the upstream pressure.
- Incorporation of a coast section into the single-group model and inclusion of the single-group model in a system program to study the stabilizing effects of the turbine and condenser on the operation of the mist lift tube.

SECTION 5.0

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Charwat, A. F. 1978 (Nov.). Studies of the Vertical Mist Transport Process for an Ocean Thermal Energy Cycle. SAN/0034-76-1. Los Angeles, CA: University of California.

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APPENDIX A

SINGLE-GROUP COMPUTER CODE BY L. LILLELEHT

```
10   !      PROGRAM FOR MIST-FLOW ANALYSIS
20   !      AS PROGRAMMED IN BASIC ON A HEWLETT-PACKARD 9845A
30   !      DESKTOP COMPUTER.
40   !      28 AUGUST, 1979
50   !
60          DIM A(5)
70          REAL M10,Mv0,M11,Mv1,M12,Mv2
80          !
90          Imax=20       !MAXIMUM NUMBER OF ITERATIONS
100         Pass=0        !FLAG FOR FIRST TIME THROUGH
110 Start:  Mv0=0         !INLET VAPOR MASS FLOW RATE (KG/S)
120         Hv0=0         !INLET VAPOR ENTHALPY (J/KG)
130         G=9.807       !ACCELERATION OF GRAVITY (M/S^2)
140         R=461.5       !GAS CONSTANT (J/KG/K)
150         Densl=1000    !LIQUID DENSITY (KG/M^3)
160         Z=0           !HEIGHT ABOVE BOTTOM OF LIFT TUBE (M)
170         DEF FNTinit(Pres)=7538/(17.777-LGT(Pres))-230
180         DEF FNPinit(Temp)=10^(17.777-7538/(Temp+230))
190         GCLEAR
200         PRINTER IS 16
210  !
220  !      INPUT
230  !
240  !      BASE CONDITIONS
250         A(1)=1
260         A(2)=1
270         A(3)=.05
280         A(4)=0
290         A(5)=0
300         Gamma=.002
310         D0=.0002
320         M10=40
330         T0=300
340         T2=280
350
360         IF Pass>=1 THEN GOTO Skip     !INPUT DATE ONLY ON FIRST TIME THROUGH
370         INPUT "INPUT DATE IN FORM DD/DD/DD",Date$
380         Pass=1
390         !
400 Skip:   INPUT "INPUT A(1) TO A(5):",A(1),A(2),A(3),A(4),A(5)
410         ! CONSTANTS TO DEFINE LIFT TUBE SHAPE
420         IF A(1)=0 THEN STOP
430         INPUT "INJECTOR AREA/LIFT TUBE AREA =",Gamma
440         INPUT "DROP DIAMETER (M) =",D0
450         D=D0
460         INPUT "MASS FLOW RATE (KG/SEC) =",M10
470         INPUT "INLET TEMPERATURE (K) =",T0
480         !
490 Fill:   T1=0
500         INPUT "FLASHDOWN TEMP. (K) = (TYPE CONT IF YOU WANT THE PROGRAM TO CA
LCULATE IT)",T1
510         Temp=T1
520         Flagtemp=0    !FLAG FOR WHETHER OR NOT FLASHDOWN TEMP. IS INPUT
530         IF Temp<1 THEN Flagtemp=1   !FLASHDOWN TEMP. CALCULATED
540         IF Temp<1 THEN Temp=T0-.1    !FIRST GUESS OF FLASHDOWN IS .1 DEGREE
550         !
560         INPUT "CONDENSER TEMPERATURE (K) =",T2
570  !      INPUT "INCREMENT IN Z (M) =",Zdel
580         Zdel=2
590  !      INPUT "CONVERGENCE LIMIT FOR PRESSURE (N/M^2) =",Delta
600         Delta=5
610  !
620  !      COMPUTE INITIAL CONDITIONS
630  !
640         H10=4193*(T0-273.15)   ! INLET LIQUID ENTHALPY
650         U10=M10/(Densl*A(1)*A(2)*Gamma)   ! LIQUID VELOCITY AT INLET
660         Ul=U10
670         Uv=Ul         ! FIRST GUESS AT VAPOR VELOCITY
680         Ul1=0         ! SET UP FOR ITERATION
690         Z=Zdel
700 Iter:   Pres=FNPinit(Temp)
710         GOSUB Values
720         Gamma1=(Alpha*Densl+(1-Alpha)*Pres/(R*Temp))/Densl
730         ! MINIMUM INJECTOR HOLE AREA/TOTAL AREA DETERMINED BY AMOUNT
740         ! OF FLASHDOWN AVAILABLE TO FILL LIFT TUBE WITH VAPOR
750         !
760 Init1:  IF Flagtemp=1 THEN GOTO Calc    !TO CALCULATE FLASHDOWN TEMP.
770         !
780         ! IF FLASHDOWN TEMP. INPUT, CHECK TO SEE IF ABLE TO FILL TUBE
790         IF Gamma1>Gamma THEN PRINT "UNABLE TO FILL LIFT TUBE WITH VAPOR"
800 !       IF Gamma1>Gamma THEN GOTO Fill    !INPUT NEW FLASHDOWN TEMP. IF NOT
810         !  ABLE TO FILL TUBE
820         GOTO Contin
830         !
840 Calc:   IF Gamma1<Gamma THEN GOTO Contin  !CONTINUE IF FLASHDOWN TEMP. IS
850         !  LOW ENOUGH.
860         Temp=Temp-.1    !IF NOT, DECREASE TEMP BY .1 AND GO BACK
870         GOTO Iter
880         !
890 Contin:T1=Temp
900         !
910         ! CHECK TO SEE IF SLIP VELOCITY IS LARGE ENOUGH TO LIFT DROPS
920         IF Uv>A1 THEN GOTO Beeper
930         Gamma1=Gamma*2
940         GOTO Init1    ! IF NOT, GO BACK AS IF UNABLE TO FILL LIFT TUBE
950         !
960 Beeper:IF ABS(Ul-Ul1)/Ul<=.01 THEN GOTO Begin !ITERATE ON INITIAL
970         ! FLASHDOWN UNTIL WITHIN 1%
980         BEEP
990         ! STORE OLD VALUE
1000        Ul1=Ul
1010        GOTO Iter
1020 !
1030 Begin:P1=Pres/100
1040        GOSUB Graph !INITIATE GRAPHICS ROUTINE
1050        !
1060        ! THIS SECTION PRINTS THE INPUT OR CALCULATED FLASHDOWN TEMP. ON
1070        ! THE GRAPH.
1080        MOVE Z+25,Temp-250
1090        CSIZE 3
1100        LINE TYPE 1
1110        LORG 2
1120        L$="INPUT"
1130        IF Flagtemp=1 THEN L$="CALCULATED"
1140        LABEL USING "K";L$," FLASHDOWN TEMP.:";Temp
1150        LINE TYPE 2
1160        !
1170 Increment:  Z=Z+Zdel    !BEGINNING OF MAIN LOOP
1180        Pprime=Pres+.5             !FIRST GUESS AT DELTA P
1190        ! STORE OLD VALUES
1200        Ul1=Ul
1210        Uv1=Uv
1220        Pres1=Pres
1230        Alpha1=Alpha
1240        I=0
1250        !
1260 Iterate:   IF I=Imax THEN CALL Err(6)
1270        Temp=FNTinit(Pprime)
1280        GOSUB Values
1290        Delp=-((Alpha1+Alpha)/2)*(G*Densl*Zdel)
```

```
1300        Delp=Delp-Densl*(Alpha*Ul*Ul-Alphal*Ul1*Ul1)/2
1310        P2=Pres1+Delp
1320        IF P2<0 THEN PRINT "NEGATIVE PRESSURE!!ALPHA1=";Alphal;"ALPHA=";Alpha
1330        IF P2<0 THEN P2=Pprime*1.02
1340        IF ABS(P2-Pprime)<=Delta THEN GOTO Converged
1350        Pprime=P2
1360        I=I+1
1370        GOTO Iterate
1380        !
1390 Converged:  Pres=P2
1400        PRINT USING "DDD,2X,DDD.D,2X,.DDDDD,2X,DD.DD,2X,DD.DD,2X,.DDDDD";Z;Te
mp;Gamma;Ul;Uv;Alpha
1410        IF Pres<=0 THEN CALL Err(5)
1420        !
1430        P1=Pres/100
1440        Temp0=Temp-273.15
1450        PLOT Z,Temp0
1460        PLOT Z,P1
1470        PLOT Z,Ul
1480        PLOT Z,Uv
1490        !
1500        IF Temp<=12 THEN GOTO Finish    !STOP WHEN TEMPERATURE IS THAT
1510        ! SPECIFIED FOR CONDENSER.
1520        !
1530        GOTO Increment      !END OF MAIN LOOP
1540        !
1550 Finish:LINE TYPE 1
1560        BEEP
1570        LDIR 0
1580        LORG 2
1590        CSIZE 2
1600        Z1=Z
1610        IF Z>250 THEN Z1=250
1620        MOVE Z1+5,P1
1630        LABEL USING "K";"PRESSURE"
1640        MOVE Z1+5,Ul
1650        LABEL USING "K";"LIQUID VEL."
1660        MOVE Z1+5,Uv
1670        LABEL USING "K";"VAPOR VEL."
1680        MOVE Z1+5,Temp0
1690        LABEL USING "K";"TEMPERATURE"
1700        !
1710        H0=4183*(T0-T2-T2*LOG(T0/T2))/G
1720        ! THEORETICAL LIFT HEIGHT FROM RDA FINAL REPORT, SEPT.,1978
1730        Eff=Z/H0            !LIFT EFFICIENCY
1740        MOVE Xmax-5,Ymax-2
1750        CSIZE 3
1760        LORG 8
1770        LABEL USING "K,Z.DDD";"LIFT EFFICIENCY =";Eff
1780        !
1790        INPUT "DO YOU WANT HARDCOPY?  TYPE YES OR NO.",H$
1800        IF H$<>"YES" THEN GOTO Fini
1810        !
1820 Finis:DUMP GRAPHICS
1830        PRINTER IS 0
1840        GOTO Output
1850 Fini: PRINTER IS 16
1860 Output:PRINT "A(1),A(2),A(3),A(4),A(5),D,ML0,T0,T1,T2,DELTA,GAMMA"
1870        PRINT A(1);A(2);A(3);A(4);A(5);D0;M10;T0;T1;T2;Delta;Gamma
1880        PRINT "INLET VELOCITY =";U10
1890        PRINT "FINAL DROP DIAMETER =";D
1900        PRINT "LIFT HEIGHT, NEGLECTING FINAL VELOCITY =";Z
1910        PRINT "THEORETICAL LIFT HEIGHT NEGLECTING INITIAL VELOCITY =";H0
1920        GOTO Start
1930        END
1940 !
1950 !
1960 Graph:    ! INITIATES GRAPHING ROUTINE
1970        PLOTTER IS 13,"GRAPHICS"
1980        GRAPHICS
1990        DEG
2000        LINE TYPE 1
2010        LOCATE 15,95,15,95
2020 !
2030        Xmin=0
2040        Xmax=250
2050        Xstep=50
2060 !
2070        Ymin=0
2080        Ymax=50
2090        Ystep=5
2100 !
2110        SCALE Xmin,Xmax,Ymin,Ymax
2120        AXES Xstep,Ystep,0,0,5,5
2130        FRAME
2140 !
2150        GOSUB Lx
2160        GOSUB Ly
2170        LDIR 0
2180        LORG 5
2190        CSIZE 3
2200        MOVE Xmax/2,Ymax+1
2210        LABEL USING "K";"MIST FLOW OPEN CYCLE OTEC - ";Date$
2220        LINE TYPE 2
2230 !
2240        Temp0=Temp-273.15
2250        PLOT Z,P1
2260        PLOT Z,Ul
2270        PLOT Z,Uv
2280        PLOT Z,Temp0
2290        RETURN
2300 !
2310 !      SUBROUTINES TO LABEL AXES
2320 !
2330 Lx:    !
2340        CSIZE 3
2350        LDIR 90
2360        LORG 8
2370        FOR X1=Xmin TO Xmax STEP Xstep
2380        MOVE X1,Ymin
2390        LABEL USING "M4DX";X1
2400        NEXT X1
2410        LORG 5
2420        LDIR 0
2430        MOVE Xmax/2,Ymin-6
2440        LABEL USING "K";"Z(METERS)"
2450        !
2460        LINE TYPE 3,15
2470        FOR I=Xmin+Xstep TO Xmax-Xstep STEP Xstep
2480        MOVE I,Ymin
2490        DRAW I,Ymax
2500        NEXT I
2510        LINE TYPE 1
2520        RETURN
2530 !
2540 Ly:    !
2550        CSIZE 3
2560        LDIR 0
2570        LORG 0
2580        FOR Y1=Ymin TO Ymax STEP Ystep
2590        MOVE Xmin,Y1
```

```
2600        LABEL USING "M4DX";Y1
2610        NEXT Y1
2620        LDIR 90
2630        LORG 5
2640        MOVE Xmin-25,Ymax/2
2650        LABEL USING "K";"V (M/S), P (100 PA), T (C)"
2660        !
2670        LINE TYPE 3,15
2680        FOR J=Ymin+Ystep TO Ymax-Ystep STEP Ystep
2690        MOVE Xmin,J
2700        DRAW Xmax,J
2710        NEXT J
2720        LINE TYPE 1
2730        RETURN
2740 !
2750 !
2760 Values:  ! COMPUTES VALUES OF VARIABLES,ITERATES TO CONVERGE ALPHA
2770        H1=4193*(Temp-273.15)
2780        Hv=2.501E6+1.834E3*(Temp-273.15)
2790        Area=A(1)*(A(2)+A(3)*Z+A(4)*Z*Z+A(5)*Z*Z*Z)
2800        Visvap=(.407*Temp-33.8)*1E-7
2810        Alpha2=Alpha    ! SET UP ITERATION
2820 Here:  Mv=M10*(H10-H1-U1*U1/2+U10*U10/2-G*Z)/(Hv-H1-U1*U1/2+Uv*Uv/2)
2830        M1=M10-Mv
2840        D=D0*(M1/M10)^(1/3)     ! RECOMPUTE DROP SIZE
2850        !
2860 !      SOLVE QUADRATIC FOR ALPHA
2870 !
2880 !      CALCULATE SLIP VELOCITY BASED ON FLOW REGIME
2890        Reyn=Pres*(Uv-U1)*D/(R*Temp*Visvap)
2900        IF Reyn<=0 THEN Reyn=1
2910        IF Reyn>=500 THEN CALL Err(4)
2920        IF Reyn>=5 THEN GOTO Transition
2930        F=24/Reyn*(1+3*Reyn/16)     !OSEEN APPROXIMATION (CF.SCHLICHTING)
2940        GOTO Skip1
2950 Transition: F=18.5/Reyn^.6
2960 Skip1:Dod=D/SQR(4*Area/3.1416)
2970        ! CORRECTION TO DRAG DUE TO OTHER DROPLETS, cf. WALLIS
2980        Ncorr=(4.45+18*Dod)/Reyn^.1
2990        IF Reyn<1 THEN Ncorr=(4.35+17.5*Dod)/Reyn^.03
3000        IF Reyn<.2 THEN Ncorr=4.65+19.5*Dod
3010        F=F/(1+Alpha)^Ncorr
3020        !
3030        A1=SQR(4*D*G*Densl*R*Temp/(3*Pres*F))  !SLIP VELOCITY
3040        B1=Mv*R*Temp/(Area*Pres)
3050        C1=-M1/(Densl*Area)
3060        IF B1=0 THEN GOTO Bzero
3070        IF C1=0 THEN GOTO Czero
3080        B1=B1-C1-A1
3090        G1=B1*B1-4*A1*C1
3100        IF G1<0 THEN CALL Err(1)
3110        Alpha=(-B1+SQR(G1))/(2*A1)
3120        Alf=(-B1-SQR(G1))/(2*A1)
3130        IF Alpha<0 THEN CALL Err(2)
3140        IF Alf<=0 THEN GOTO Final
3150        Alpha=Alf
3160        GOTO Final
3170 Bzero:Alpha=C1/A1
3180        GOTO Final
3190 Czero:Alpha=(A1-B1)/A1
3200        !
3210        ! CHECK CONVERGENCE,MAKE FINAL CALCULATIONS
3220 Final:IF (Alpha>.5) AND (Z>Zdel) THEN CALL Err(7)
3230        Uv=Mv*R*Temp/(Pres*Area*(1-Alpha))
3240        U1=M1/(Densl*Area*Alpha)
3250        IF U1<0 THEN CALL Err(3)
3260        IF ABS((Alpha2-Alpha)/Alpha)<=.01 THEN RETURN
3270        Alpha2=Alpha
3280        GOTO Here     ! IF NOT CONVERGED, TRY AGAIN
3290 !
3300        SUB Err(I)
3310 !      PRINTER IS 16
3320        IF I=1 THEN PRINT "GRADIENT FOR ALPHA NEGATIVE"
3330        IF I=2 THEN PRINT "ALPHA LESS THAN ZERO"
3340        IF I=3 THEN PRINT "LIQUID VELOCITY LESS THAN ZERO"
3350        IF I=4 THEN PRINT "REYNOLD'S NUMBER GREATER THAN 500"
3360        IF I=5 THEN PRINT "PRESSURE LESS THAN 0."
3370        IF I=6 THEN PRINT "FAILED TO CONVERGE"
3380        IF I=7 THEN PRINT "ALPHA GREATER THAN .5"
3390        PRINT "PROGRAM ABORTED"
3400        STOP
3410        SUBEND
```

APPENDIX B

PRESENT MULTIGROUP COMPUTER CODE

```
00080 PRINT " "
00090 PRINT " "
00100 PRINT "PROGRAM MIST - 50 GROUP MODEL OF MIST FLOW OTEC"
00110 PRINT "OUTPUT PRINTED FOR GROUPS WITH >1 PERCENT OF THE MASS FLOW "
00120 PRINT "SQUISHING OCCURS WHEN MORE THAN 7 GROUPS EACH HAVE"
00130 PRINT "      MORE THAN 1 PERCENT OF THE FLOW."
00140 PRINT " "
00150 DIM A(50,50),P(3,3),C(50),D(50),B(3),F(50,50),G(50),H(3,3),I(3)
00160 DIM M(50),N(50),Q(50),S(50),U(50),V(50)
00170 LET Z=0.
00180 LET P9=3.141593
00190 LET G=9.8066
00200 REM  W IS WATER FLOW RATE (KG/S)
210 LET W=1240
00220 REM  P0 IS THE INITIAL PRESSURE (BAR)
230 LET P0=0.1
00240 REM  T0 IS INITIAL TEMPERATURE (K)
00250 LET T0=25.
00260 LET T0=T0+273.15
00270 REM  A0 IS TOTAL CROSS SECTION OF ALL ORIFICES
00280 LET A0=.2
00290 REM  A3,A4,A5,A6,A7 ARE CONSTANTS THAT DETERMINE THE SHAPE OF THE
00300 REM  LIFT TUBE - A=A3 +A4*Z +A5*Z^2 +A6*Z^3 +A7*Z^4.
00310 LET A3=P9*10.*10./4.
00320 LET A4=0.
00330 LET A5=0.
00340 LET A6=0.
00350 LET A7=0.
00360 LET A=FNA(Z,0,0,A3,A4,A5,A6,A7)
00370 PRINT "A=";A3;" +Z*";A4;" +Z^2*";A5;" +Z^3*";A6;" +Z^4*";A7
00380 PRINT " "
00390 LET V3=FNI(0)
00400 REM  I1 SPECIFIES THE NUMBER OF DROPLET SIZES.
00410 LET I1=5
00420 LET P1=FNP(T1,0,0,0,0,0,0,0,0,0,0,0)
00430 LET V1=FNW(P1,T1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
00440 LET V2=FNV(P1,T1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
00450 LET E1=FNN(T1,0,0,0,0,0,0,0,0,0,0,0,0)
00460 LET S=FNS(T1,0,0,0,0,0,0,0,0,0)
00470 LET S0=(1-X)*S1+X*S2
00480 LET R1=1/V1
00490 LET R2=1/V2
00500 LET W2=X*W
00510 LET W1=W-W2
00520 LET A2=1
00530 LET A=FNA(Z,0,0,A3,A4,A5,A6,A7)
00540 LET V6=W2/R2/A/A2
00550 REM  D0 IS THE BASE DROPLET DIAMETER AT THE INLET (M)
00560 LET D0=1.5E-4
00570 REM  M9=MASS OF BASE SIZE DROP
00580 LET M9=R1*P9*(D0^3)/6.
00590 FOR I=1 TO 50
00600 LET D(I)=D0*(I^(1/3))
00610 LET M(I)=I*M9
00620 LET V(I)=V3
00630 LET U(I)=V(I)
00640 NEXT I
00650 REM  INITIALIZATION OF DROP SIZE DISTRIBUTION
00660 REM  DROP SIZES INPUT AS A DISTRIBUTION WITH SMALLEST SIZE D(1)
00670 REM   AND NUMBER OF SIZES I1.
00680 LET V4=0.
00690 FOR I=1 TO I1
00700 READ N(I)
00710 LET V4=V4 + P9*N(I)*D(I)^3)/6.
00720 REM  VOLUME OF INPUT DISTRIBUTION OF DROPS
00730 NEXT I
00740 REM  V4=RATIO OF REQUIRED TO INPUT MASS FLOW
00750 LET V4=W1/V4/R1
00760 FOR I=1 TO I1
00770 REM  CORRECT N(I) SO THAT CONTINUITY IS SATISFIED
00780 LET N(I)=N(I)*V4
00790 NEXT I
00800 DATA 37.,104.,47.,7.,7.
00810 FOR I=I1+1 TO 50
00820 LET N(I)=0.
00830 NEXT I
00840 PRINT " "
00850 PRINT "Z (M)","P (BAR)","T (C)","X","VOID FRACTION"
00860 PRINT "V-STEAM (M/S)","C (M/S)","S0 (KJ/KG K)","S (KJ/KG K)","   ERROR"
00870 PRINT "I","N (1/S)","MASS " "V (M/S)","D (M)"
00880 PRINT " "," ","PERCENT"
00890 PRINT " "
00900 LET T=T1
00910 LET P=P1
00920 LET W3=I1
00930 REM  BEGINNING OF MAIN LOOP ********************************
00940 REM  SET UP STEP SIZE
00950 LET Z9=100.
00960 FOR I=1 TO I1
00970 LET Z9=MIN(Z9,V(I))
00980 NEXT I
00990 IF Z9<10. THEN 01020
01000 LET Z9=2.0
01010 GO TO 01060
01020 IF Z9<5 THEN 01050
01030 LET Z9=.5
01040 GO TO 01060
01050 LET Z9=Z9*Z9/2./G
01060 LET Z1=Z9
01070 LET Z1=MAX(Z1,.01)
01080 LET A=FNA(Z,0,0,A3,A4,A5,A6,A7)
01090 LET N4=0
01100 FOR I=1 TO I1
01110 LET V(I)=U(I)
01120 IF V(I)>.1 THEN 01190
01130 PRINT "RAINOUT FOR DROPLET GROUP ";I;",DIAM.=";D(I)
01140 PRINT "    Z                    P                    T                    X                    V"
01150 PRINT Z,P,T-273.15,X,V(I)
01160 PRINT "RAINOUT IS ASSUMED IF ONE DROPLET SIZE"
01170 PRINT "VELOCITY BECOMES LESS THAN .1 M/S"
01180 STOP
01190 REM
01200 REM  CALCULATION OF DRAG COEFFICIENT OF INDIVIDUAL DROPLETS C(I)
01210 LET C(I)=FNC(D(I),0)
01220 IF V(I)=0 THEN 01240
01230 LET N4=N4+M(I)*N(I)/V(I)
01240 NEXT I
01250 REM  A2=VOID FRACTION
01260 LET A2=1-N4/R1/A
01270 LET V6=W2/R2/A/A2
01280 REM  R=AVERAGE DENSITY
01290 LET R=R2*A2+R1*(1-A2)
01300 REM  NUMBER OF COALESCENCE F(I,J)
01310 FOR I=1 TO I1
01320 FOR J=1 TO I1
01330 REM  A(I,J)=COLLISION CROSS SECTION
01340 LET A(I,J)=P9*(D(I)+D(J))^2/4.
01350 REM  F(I,J)=COLLISION FREQUENCY BETWEEN SPECIES I AND J /UNIT LENGTH
```

```
01360 LET F(I,J)=0
01370 IF (V(I)*V(J ))=0 THEN 01400
01380 LET F(I,J)=N I)*N(J)/(A*V(I)*V(J))*ABS(V(I -V(J))*A(I,J)
01390 LET F(I,J)=F I,J)*FNE(D(I),D(J),I,J,0,0)
01400 NEXT J
01410 NEXT I
01420 REM  S(K)=MASS SOURCE OF SPECIES K PER UNIT LENGTH FROM COLLISIONS
01430 LET S(1)=0.
01440 LET S(2)=0.
01450 IF I1<3 THEN 01530
01460 FOR K=3 TO I.
01470 LET S(K)=0
01480 FOR I=1 TO INT(K/2.)
01490 LET J=K-I
01500 LET S(K)=S(K)+F(I,J)
01510 NEXT I
01520 NEXT K
01530 REM
01540 REM  SET UP MAXIMUM STEP SIZE VARIABLE
01550 LET Z2=Z9
01560 REM  G(K)=NUMBER OF COLLISIONS PER UNIT LENGTH BETWEEN K AND ALL OTHERS
01570 FOR K=1 TO I1
01580 LET G(K)=0
01590 FOR J=1 TO I1
01600 LET G(K)=G(K)+F(K,J)
01610 NEXT J
01620 NEXT K
01630 FOR K=1 TO I1
01640 IF G(K)*Z1<=N(K) THEN 01690
01650 LET Z0=N(K)/G(K)
01660 IF Z0>Z2 THEN 01690
01670 LET Z2=Z0
01680 REM  FIND MAXIMUM ALLOWABLE STEP SIZE
01690 NEXT K
01700 IF Z2>=Z1 THEN 01730
01710 LET Z1=Z2
01720 GO TO 01630
01730 REM
01740 FOR K=1 TO I1
01750 REM  CALCULATION OF NEW DROPLET NUMBERS N(K) OF SPECIES K
01760 LET O(K)=N(K)
01770 LET N(K)=O(K)-G(K)*Z1
01780 IF N(K)>=0 THEN 01810
01790 LET N(K)=0.
01800 LET W3=W3+1
01810 LET N(K)=N(K)+S(K)*Z1
01820 NEXT K
01830 REM  CALCULATION OF NEW DROPLET VELOCITY U(K) OF SPECIES K
01840 FOR K=1 TO I1
01850 LET T2=(O(K)-G(K)*Z1)*V(K)*M(K)
01860 LET T5=0
01870 IF V(K)=0 THEN 01990
01880 LET T5=P1*N(K)*P9*(D(K)^3)/(6.*V(K))
01890 LET T3=0
01900 FOR I=1 TO INT(K/2.)
01910 LET J=K-I
01920 LET T3=T3+F(I,J)*(V(I)*M(I)+V(J)*M(J))*Z1
01930 NEXT I
01940 LET T4=0
01950 IF V(K)=0 THEN 02120
01960 LET T4=N(K)*Z1*C(K)*P9*R2*(V6-V(K))*ABS(V6-V(K))*(D(K)^2)/(V(K)*8.)
01970 LET T4=T4-N(K)/V(K)*Z1*M(K)*G
01980 IF N(K)<=0 THEN 02120
01990 LET U(K)=(T2+T3+T4-T5)/(N(K)*M(K))
02000 REM
02010 REM
02020 REM   IF CHANGE IN VELOCITY IS TOO LARGE, REDUCE DELTA Z
02030 IF(ABS(U(K)-V(K))/V(K)<.2) OR (V(K)<2.) THEN 02120
02040 LET Z1=Z1/1.5
02050 REM RESET N(K) AND V(K)
02060 FOR K=1 TO I1
02070 LET N(K)=O(K)
02080 LET U(K)=V(K)
02090 NEXT K
02100 GO TO 01740
02110 REM
02120 NEXT K
02130 REM  CALCULATION OF NEWLY CREATED DROPLET SPECIES
02140 IF I1=1 THEN 02390
02150 LET I3=I1+1
02160 LET I1=2*I1-1
02170 IF I1<=50 THEN 02190
02180 LET I1=50
02190 REM
02200 FOR K=I3 TO I1
02210 LET M(K)=K*M(1)
02220 LET N(K)=0
02230 LET U1=0
02240 FOR I=(K-I3+1) TO INT(K/2.)
02250 LET J=K-I
02260 LET N(K)=N(K)+F(I,J)*Z1
02270 LET U1=U1+F(I,J)*(M(I)*U(I)+M(J)*U(J))
02280 NEXT I
02290 LET D(K)=(M(K)/R1*6./P9)^(1/3)
02300 IF N(K)=0 THEN 02320
02310 LET U(K)=U1*Z1/N(K)/M(K)
02320 NEXT K
02330 REM  SET UP I1 BY FINDING FIRST NON-ZERO SPECIES
02340 REM  COUNTING DOWN FROM 50.
02350 FOR K=50 TO 1 STEP -1
02360 IF N(K)>0 THEN 02380
02370 NEXT K
02380 LET I1=K
02390 REM  MATRIX SOLUTION OF CONSERVATION EQUATIONS
02400 LET P=FNP(T,0,0,0,0,0,0,0,0,0,0)
02410 LET P2=FNP(T-1,0,0,0,0,0,0,0,0,0,0)
02420 LET V3=FNW(P2,T-1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
02430 LET H3=H1
02440 LET S3=S1
02450 LET V1=FNW(P,T,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
02460 LET V8=FNV(P2,T-1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
02470 LET H8=H2
02480 LET S8=S2
02490 LET V2=FNV(P,T,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
02500 LET H5=(H1-H3)/(P-P2)*0.01
02510 REM  COMPUTE DH2/DP
02520 LET H6=(H2-H8)/(P-P2)*0.01
02530 REM  COMPUTE DR2/DP
02540 LET R6=(1/V2-1/V8)/(P-P2)*1.0E-5
02550 LET Q1=0
02560 LET Q2=0
02570 LET Q3=0
02580 LET Q4=0
02590 LET Q5=0
02600 LET Q6=0
02610 LET Q7=0
02620 FOR I=1 TO I1
02630 LET Q1=Q1+O(I)*M(I)*V(I)
```

```
02640 LET Q2=Q2+C(I)*M(I)
02650 LET Q3=Q3 +C(I)*M(I)*(H1*1000.+V(I)*V(I)/2.)
02660 LET Q4=Q4+M(I)*(N(I)-D(I))*(V(I)^2)/2.
02670 LET Q5=Q5+C(I)*M(I)*V(I)*(U(I)-V(I))
02680 LET Q6=Q6+C(I)*M(I)*(U(I)-V(I))
02690 LET Q7=Q7+M(I)*V(I)*(N(I)-D(I))
02700 NEXT I
02710 REM  PLACING THE COEFFICIENTS IN THE MATRIX
02720 LET B(1,1)=-1/X
02730 LET B(1,2)=1/R2*R6
02740 LET B(1,3)=1/V6
02750 LET F(1)=-A1/A
02760 LET B(2,1)=W*(V6-Q1/Q2)
02770 LET B(2,2)=A
02780 LET B(2,3)=X*W
02790 LET F(2)=-R*G*A*Z1-Q6-Q7
02800 LET B(3,1)=W*(H2*1000.+(V6^2)/2.-Q3/Q2)
02810 LET B(3,2)=X*W*H5+(1-X)*W*H5
02820 LET B(3,3)=X*W*V6
02830 LET F(3)=-G*W*Z1-Q5-Q4
02840 MAT H=INV(B)
02850 MAT I=H*F
02860 LET X1=I(1)
02870 LET P1=I(2)
02880 LET V8=I(3)
02890 LET T6=(V2-V1)/(S2-S1)*P1*1.0E-3
02900 LET T=T+T6
02910 LET X=X+X1
02920 LET V6=V6+V8
02930 LET W2=X*W
02940 LET V9=W2/R2/A/A2
02950 LET V6=V9
02960 LET W1=(1-X)*W
02970 LET P=FNP(T,0,0,0,0,0,0,0,0,0,0,C)
02980 LET V1=FNW(P,T,0,0,0,0,0,0,0,0,0,0,0,C,0,0,0,0,0)
02990 LET V2=FNV(P,T,0,0,0,0,0,0,0,0,0,0,0,C,0,0,0,0,0,C)
03000 LET E1=FNN(T,0,0,0,0,0,0,C,0,0,0,0,0,C)
03010 LET S=FNS(T,0,0,0,0,0,0,0,0,0)
03020 LET P1=1/V1
03030 LET R2=1/V2
03040 LET Z=Z+Z1
03050 FOR I=1 TO I1
03060 LET M1=-M(I)/Q2*W*X1
03070 LET M(I)=M(I)+M1
03080 LET D(I)=(M(I)*6./P1/P9)^(1/3)
03090 NEXT I
03100 REM  CALCULATE ERROR IN MASS FLOW.
03110 LET W4=0
03120 FOR K=1 TO 50
03130 LET W4=W4 +N(K)*M(K)
03140 NEXT K
03150 LET W4=100*(1 -(W4 +X*W)/W)
03160 IF W3<8 THEN 03450
03170 REM  DON"T SQUISH IF SPECTRUM HAS REACHED FULL DEVELOPMENT.
03180 IF FNE(D(1),D(50),1,50,0,0)<1.E-7 THEN 03450
03190 REM  SQUISH PRESENT DROP SPECTRUM INTO I=1-25, DOUBLING THE MASS INCREMENT
03200 REM  CONSERVE MASS AND MOMENTUM
03210 LET M9=M(2)
03220 FOR J=1 TO 25
03230 LET I=2*J
03240 LET K=I-1
03250 IF (N(K)+N(I))=0 THEN 03270
03260 LET U(J)=(M(K)*N(K)*U(K)+M(I)*N(I)*U(I))/(M(K)*N(K)+M(I)*N(I))
03270 LET N(J)=N(I)+N(K)*M(K)/M(I)
03280 LET M(J)=J*M9
03290 LET D(J)=(6.*M(J)/R1/P9)^(1/3)
03300 NEXT J
03310 REM  CLEAR THE SPECTRUM FROM J=26 TO 50
03320 FOR J=26 TO 50
03330 LET N(J)=0.
03340 LET M(J)=J*M9
03350 LET D(J)=(6.*M(J)/P9/R1)^(1/3)
03360 NEXT J
03370 REM RESET I1 TO FIRST NON-ZERO GROUP FROM TOP
03380 FOR J=25 TO 1 STEP -1
03390 IF N(J)>0 THEN 03420
03400 NEXT J
03410 PRINT "ERROR-- NO NON-ZERO GROUPS"
03420 LET I1=J
03430 REM
03440 PRINT "SQUISHED SPECTRUM - NEW MASS INCREMENT ="; M9
03450 REM  PRINTOUT
03460 REM  CONTINUE TO PRINT RESULTS
03470 PRINT Z,P,T-273.15,X,A2
03480 LET C6=SQR(R2/P1/A2/(1-A2))*SQR(599.92*T)
03490 PRINT V6,C6,S0,(1-X)*S1+X*S2,W4
03500 PRINT " "
03510 FOR I=1 TO I1-1
03520 REM  CONTROL IF WEBERNUMBER EXCEEDS 12
03530 LET W5=R2*D(I)*(V6-V(I))^2/S
03540 IF W5<=12 THEN 03560
03550 PRINT "WE>12, GROUP";I
03560 IF N(I)*M(I)<.01*W THEN 03590
03570 PRINT I,N(I),N(I)*M(I)/W*100,U(I),D(I)
03580 LET W3=I
03590 NEXT I
03600 PRINT "LAST GROUP IN SPECTRUM"
03610 PRINT I1,N(I1),N(I1)*M(I1)/W*100,U(I1),D(I1)
03620 LET J4=0
03630 PRINT " "
03640 PRINT " "
03650 REM  STOP WHEN T<8. CELCIUS
03660 IF T-273.15<8. THEN 03690
03670 REM OTHERWISE,GO BACK TO TOP OF LOOP
03680 GO TO 00930
03690 PRINT "TEMPERATURE LESS THAN 8 CELCIUS--PROGRAM STOP"
03700 STOP
03710 DEF FNC(D,R)
03720 REM  CALCULATION OF DRAG COEFFICIENT
03730 LET R=R2*(ABS(V6-V(I)))*D/S2
03740 IF R>1000 THEN 03770
03750 LET D=24.*(1.+.15*R^.687)/R
03760 GO TO 03780
03770 LET D=0.44
03780 FNC=D
03790 FNEND
03800 DEF FNA(Z,D1,D,A0,A2,A3,A4,A5)
03810 REM  CALCULATION OF CROSS SECTION AS A FUNCTION OF LENGTH
03820 REM  A0=AREA OF LIFT TUBE BOTTOM (M^2)
03830 REM  D1=DIAMETER AT LIFT TUBE BOTTOM (M)
03840 LET D1=SQR(4.*A0/3.141593)
03850 REM A1=DA/DZ
03860 LET A1=A2 +2*A3*Z +3*A4*Z*Z +4*A5*Z^3
03870 FNA=(A0 +A2*Z +A3*Z^2 +A4*Z^3 +A5*Z^4)
03880 FNEND
03890 DEF FNP(T,T2,Y,K,A,B,C,D,E,F,X,A1)
03900    REM  CALCULATION OF THE TEMPERATURE PRESSURE RELATION OF WATER/STEAM
03910    REM  AT SATURATION LINE
```

```
03920     LET T2=T+0.01
03930     LET Y=374.11-(T-273.15)
03940     LET K=2.937E+5
03950     LET A=5.426651
03960     LET B=-2005.1
03970     LET C=1.3869E-4
03980     LET D=1.1965E-11
03990     LET E=-0.0044
04000     LET F=-0.0057148
04010     LET X=T2^2 - K
04020     IF ABS(Y)>10 THEN 04040
04030     LET X=0
04040     LET T=T/647.3
04050     LET A1=A +B/T2 +C*X/T2*(10^(D*X*X)-1.)+E*1C^(F*Y^1.25)
04060     LET A1=1.01325*10^A1 +(T-.422)*(.577-T)*EXP(-12.*T^4)*9.80665E-3
04070     LET T=T*647.3
04080      FNP=A1
04090 FNEND
04100 DEF FNV(P,T,P0,R,A,B,C,D,E,F,V1,V3,V4,H0,I1,H1,S0,S1,S3,S4)
04110     REM  STEAM TABLE OF SATURATED AND SUPERHEATED STEAM
04120     REM  ALL VALUES ARE GIVEN IN SI-UNITS
04130      REM  221.287=CRITICAL PRESSURE (BAR)
04140      REM  647.3=CRITICAL TEMPERATURE (K)
04150     LET T=T/647.3
04160     LET P=P/221.287
04170     LET P0=2.765-5
04180     REM  CONSTANTS FOR SPEC.VOLUME
04190     LET R=1.34992E-2
04200     LET A=4.7331E-3
04210     LET B=2.93945E-3
04220     LET C=4.35507E-6
04230     LET D=6.70126E-4
04240     LET E=3.17362E-5
04250     LET F=8.06867E-5
04260     REM  CALCULATION OF SPEC.VOLUME OF STEAM
04270     LET V1=R*T/P
04280      LET V2=(A-E*(1.55108-P)*T^(2*2.82))/T^2.82
04290      LET V3=(B-(1.26591*P-T^3)*D*P)/T^14 + C/T^32
04300      LET V3=V3*P*P
04310     LET V4=(1-1.32735*P)*F*T
04320     LET V2=V1-V2-V3-V4
04330     REM  CALCULATION OF SPEC.ENTHALPY OF STEAM
04340      LET H0=20.03327E2 +11.698648E2*T +(-8.05536*T^2)
04350      LET H0=H0 +73.76581*T^3 +(-13.02568*T^4)
04360     LET I1=34.1862*647.3
04370      LET H1=(3.82*A/T^2.82 + 1.82*E*(1.55108-P/2.)*T^2.82)*P
04380      LET H2=(5.*B-3.*(1.26591*P-T^3)*D*P)/T^14
04390      LET H2=(H2 +11.*C/T^32)*P^3
04400      LET H2=H0 -I1*(H1+H2)
04410     REM  CALCULATION OF SPEC.ENTROPY
04420      LET S0=1.807299*LOG(T) +10.696236 -2.488914E-2*T +.1709387*T*T
04430      LET S0=S0 -2.683287E-2*T^3
04440     LET I1=I1/647.3
04450     LET S1=I1*R*LOG(P/P0)
04460      LET S3=2.82*A/T^3.82 +2.82*E*(1.55108-P/2.)*T^1.82
04470     LET S4=F*(1-1.32735*P/2)
04480     LET S3=(S3-S4)*P
04490      LET S4=(14./3.*B -(14./5.*1.26591*P -11./4.*T^3)*D*P)/T^15
04500      LET S4=(S4 +32.*C/3./T^33)*P^3
04510     LET S2=S0-S1-I1*(S3+S4)
04520     LET T=T*647.3
04530     LET P=P*221.287
04540 FNV=V2
04550 FNEND
04560 DEF FNW(P,T,H,K,L,M,N,L1,N1,U,W,V2,V3,V,V9,H0,H2,S0,S2)
04570     REM  STEAM TABLE OF SUBCOOLED AND SATURATED WATER
04580      REM  221.287=CRITICAL PRESSURE (BAR)
04590      REM  647.3=CRITICAL TEMPERATURE (K)
04600     LET T=T/647.3
04610     LET P=P/221.287
04620     REM  CONSTANTS FOR SPEC.VOLUME
04630     LET H=1.139706E-4
04640     LET K=9.949927E-5
04650     LET L=7.241165E-5
04660     LET M=7.676521E-1
04670     LET N=1.052358E-11
04680     LET H1=1.999850E+5
04690     LET L1=1.362926E+16
04700     LET N1=6.537154E-1
04710     REM  CALCULATION OF SPEC.VOLUME
04720      LET U=3.7E? -3.122199E8*T*T -H1*T^(-6)
04730      LET W=U +(1.72*U*U +L1*(P-1.500705*T))^(.5)
04740      LET V1=.417/W^(1/3.4) -H +K*T
04750      LET V1=V1 +(N1-T)^2*(L +(N1-T)^?*M)
04760      LET V1=V1 -(N*(62.5 +13.10268*P +P*P))/(1.5108E-5+T^11)
04770     REM  CONSTANTS FOR SPEC.ENTHALPY
04780       LET H0=-?.7444869?E4 +4.6645335?E5*T -2.66687677E6*T*T
04790      LET H0=H0 +9.03027153E6*T^3 -1.97694002E7*T^4 +2.89452399E7*T^5
04800       LET H0=H0 -2.83099327E7*T^6 +1.78089426E7*T^7 -6.53467601E6*T^8
04810       LET H0=H0 +1.06519853E6*T^9
04820      LET V=-2.*3.122199E8*T^2 +6.*H1/T^6
04830     REM  CALCULATION OF SPEC. ENTHALPY
04840     LET H1=(.58620689*W-.41666667*(3.4*U-V))*W
04850      LET H1=2.*.417/L1/W^(1/3.4)*(H1+L1*1.500705/2.*T -.72*V*U)
04860      LET H2=-H +(N1-T)*(L*(N1+T) +M*(N1-T)^8*(N1+9.*T))
04870      LET H1=H2*P +H1
04880      LET H2=(N*(1.5108E-5 +12.*T^11))/(1.5108E-5 +T^11)^2
04890     LET H2=H2*(62.5+(13.10268/2+P/3)*P)*P
04900     LET H1=H0+34.1862*647.3*(H1-H2)
04910     REM  CONSTANTS FOR SPEC. ENTROPY
04920       LET S0=7.20613887E2*LOG(T) +2.20637861E3 -8.24000235E3*T
04930       LET S0=S0 +2.092601E4*T*T -4.07217676E4*T^3 +5.59038325E4*T^4
04940       LET S0=S0 -5.24824968E4*T^5 +3.20980993E4*T^6 -1.15374651E4*T^7
04950       LET S0=S0 +1.?5130285E3*T^8
04960     REM  CALCULATION OF SPEC. ENTROPY
04970     LET S1=.41666667*V*W+L1*1.500705/2.*T-0.72*V*U
04980     LET S1=S1*2.*.417/L1/T/W^(1/3.4)
04990     LET S2=(L +5.*M*(N1-T)^9)*(N1-T)*2. -K
05000     LET S1=S2*P +S1
05010     LET S2=11.*T^10*N/(1.5108E-5+T^11)^2
05020     LET S2=S2*(62.5+(13.10268/2+P/3)*P)*P
05030     LET S1=S0+34.1862*(S1-S2)
05040     LET T=T*647.3
05050     LET P=P*221.287
05060 FNW=V1
05070 FNEND
05080 DEF FNN(T,A1,A2,A3,B1,B2,B3,C1,C2,C3,T1,V1,V,E3)
05090     REM  CALCULATION OF DYNAMIC VISCOSITY
05100     REM  FOR WATER AND STEAM
05110     REM  CONSTANTS:
05120     LET A1=241.4
05130     LET A2=0.3928209486
05140     LET A3=2.162830218E-1
05150     LET B1=263.4511
05160     LET B2=0.4219836243
05170     LET B3=80.4
05180     LET C1=586.1198738
05190     LET C2=1204.753943
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05200     LET C3=B2
05210     LET T1=647.3
05220     LET T=T/T1
05230     LET V1=0.00317
05240     REM  CALCULATION OF DYN.VISCOSITY OF WATER
05250     LET E1=A2/(T-A3)
05260     LET E1=A1*10^E1*1.E-7
05270     REM  CALCULATION OF DYN.VISCOSITY OF STEAM
05280     LET E2=B1*(T-B2)+B3
05290     LET V=V2/V1
05300     LET E3=E2-1/V*(C1-C2*(T-C3))
05310     LET E2=E3*1.0E-7
05320     LET T=T*T1
05330 FNN=E1
05340 FNEND
05350 DEF FNS(T,A1,A2,A3,A4,A5,B,T1,T2,S0)
05360     REM  CALCULATION OF SURFACE TENSION
05370     REM  VALIDITY REGION UP TO CRIT.TEMP.
05380     LET A1=1.160936807E-1
05390     LET A2=1.121404688E-3
05400     LET A3=-5.752805180E-6
05410     LET A4=1.286274650E-8
05420     LET A5=-1.149719290E-11
05430     LET B=0.83
05440     LET T1=647.3
05450     LET T2=T1-T
05460 LET S0=A1*T2^2
05470 LET S0=S0/(1.+B*T2)
05480 LET S0=S0+A2*T2^2 +A3*T2^3 +A4*T2^4 +A5*T2^5
05490 FNS=S0*1.E-3
05500 FNEND
05510 DEF FNT(P,P1,T,J)
05520     REM  CALCULATION OF THE PRESSURE TEMPERATURE RELATION
05530     REM  OF WATER/STEAM AT SATURATION
05540 LET J=0
05550     LET P1=P
05560     IF P1<0.1 THEN 05900
05570     IF P1<0.2 THEN 05880
05580     IF P1<0.5 THEN 05860
05590     IF P1<1.0 THEN 05840
05600     IF P1<2.0 THEN 05820
05610     IF P1<5.0 THEN 05800
05620     IF P1<10.0 THEN 05780
05630     IF P1<20.0 THEN 05760
05640     IF P1<50.0 THEN 05740
05650     IF P1<100.0 THEN 05720
05660     IF P1<200.0 THEN 05700
05670     LET T=638.85
05680     LET T=T+273.15
05690     GO TO 05910
05700     LET T=584.11
05710     GO TO 05910
05720     LET T=537.06
05730     GO TO 05910
05740     LET T=485.52
05750     GO TO 05910
05760     LET T=453.03
05770     GO TO 05910
05780     LET T=424.99
05790     GO TO 05910
05800     LET T=393.38
05810     GO TO 05910
05820     LET T=372.75
05830     GO TO 05910
05840     LET T=354.49
05850     GO TO 05910
05860     LET T=333.24
05870     GO TO 05910
05880     LET T=318.98
05890     GO TO 05910
05900     LET T=273.15
05910     LET P=FNP(T,0,0,0,0,0,0,0,0,0,0,0)
05920 IF J=1 THEN 05990
05930 IF P>P1 THEN 05960
05940 LET T=T+0.1
05950 GO TO 05910
05960 LET T=T-0.1
05970 LET J=1
05980 GO TO 05910
05990 IF P>P1 THEN 06020
06000 LET T=T+0.01
06010 GO TO 05910
06020 FNT=T
06030 FNEND
06040 DEF FNI(U0)
06050  REM  CALCULATION OF ENTRANCE CONDITIONS
06060 LET V0=FNW(P0,T0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
06070 LET H0=H1
06080 LET S0=S1
06090 LET U0=W/A0*V0
06100 LET P1=P0 -.5*U0*U0/V0*1.E-5
06110 LET T1=FNT(P1,0,0,0)
06120 LET V1=FNW(P1,T1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
06130 LET V2=FNV(P1,T1,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0,0)
06140 LET X=(H0-H1)/(H2-H1)
06150 IF X>0 THEN 06170
06160 PRINT "X<0 "
06170 LET A=FNA(Z,0,0,A3,A4,A5,A6,A7)
06180 LET V6=X*W*V2/A
06190 PRINT "W=";W,"A0=";A0
06200 PRINT "P0=";P0,"T0=";T0-273.15,"V(F)=";U0
06210 PRINT "P1=";P1,"T1=";T1-273.15,"V(G)=";V6
06220 IF X>0 THEN 06240
06230 STOP
06240 FNI=U0
06250 FNEND
06260 DEF FNF(D1,D2,I,J,S0,E9)
06270 REM  CALCULATES COALESCENCE EFFICIENCY BASED ON DROP DIAMETERS
06280 IF D1>D2 THEN 06370
06290 REM  MAKE SURE D1 IS THE LARGER DROP
06300 LET E9=D2
06310 LET D2=D1
06320 LET D1=E9
06330 REM  MAKE SURE I IS THE INDEX CORRESPONDING TO THE LARGER DROP
06340 LET E9=J
06350 LET J=I
06360 LET I=E9
06370 REM  CHANGE TO RADII IN MICRONS
06380 LET D1=D1*1.E6/2.
06390 LET D2=D2*1.E6/2.
06400 IF D1>D2 THEN 06450
06410 REM  IF D1=D2, RETURN WITH E9=1 SINCE THEY WONT COLLIDE ANYWAY
06420 LET E9=0.
06430 GO TO 07060
06440 REM  BRANCH TO DIFFERENT CALCULATIONS DEPENDING ON RATIO OF DROP RADII
06450 LET R0=D1/D2
06460 IF R0>3. THEN 06960
06470 IF R0>2.5 THEN 06810
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06480 IF RO>2.0 THEN 06700
06490 IF RO>1.5 THEN 06590
06500 REM  RO=1.0-1.5
06510 IF D1<80. THEN 06570
06520 IF D1<600. THEN 06550
06530 LET E9=.7*(D1-600.)/2800.
06540 GO TO 07060
06550 LET E9=0.
06560 GO TO 07060
06570 LET E9=.1
06580 GO TO 07060
06590 REM  RO=1.5-2.0
06600 IF D1<80. THEN 06570
06610 IF D1<200. THEN 06550
06620 IF D1<400. THEN 06580
06630 IF D1<700. THEN 06660
06640 LET E9=.2 + .6*(D1-700.)/2300.
06650 GO TO 07060
06660 LET E9=.2
06670 GO TO 07060
06680 LET E9=.2*(D1-200)/200.
06690 GO TO 07060
06700 REM  RO=2.0-2.5
06710 IF D1<70. THEN 06570
06720 IF D1<200. THEN 06550
06730 IF D1<350. THEN 06790
06740 IF D1<1000. THEN 06770
06750 LET E9=.5*(D1-1000.)/2000. + .3
06760 GO TO 07060
06770 LET E9=.3
06780 GO TO 07060
06790 LET E9=.3*(D1-200.)/150.
06800 GO TO 07060
06810 REM  RO=2.5-3.0
06820 IF D1<70. THEN 06570
06830 IF D1<180. THEN 06550
06840 IF D1<250. THEN 06940
06850 IF D1<600. THEN 06770
06860 IF D1<800. THEN 06920
06870 IF D1<2000. THEN 06900
06880 LET E9=.6 + .2*(D1-2000.)/1500.
06890 GO TO 07060
06900 LET E9=.2 + .4*(D1-800.)/1200.
06910 GO TO 07060
06920 LET E9=.3 - .1*(D1-600.)/200.
06930 GO TO 07060
06940 LET E9=.3*(D1-180.)/70.
06950 GO TO 07060
06960  REM  RO=3.0-4.0
06970 IF D1<80. THEN 06570
06980 IF D1<180. THEN 06550
06990 IF D1<400. THEN 07050
07000 IF D1<800. THEN 07030
07010 LET E9=.1 + .7*(D1-800.)/3200.
07020 GO TO 07060
07030 LET E9=.5 - .4*(D1-400.)/400.
07040 GO TO 07060
07050 LET E9=.5*(D1-180.)/220.
07060 REM  FINISH UP
07070 IF ((D1^3 + D2^3)^(1/3)) < 2500. THEN 07100
07080 REM  ALLOW NO GROWTH PAST 2.5MM BECAUSE FLOW IS TURBULENT
7090 LET E9=1.
07100 LET D1=D1*2.E-6
07110 LET D2=D2*2.E-6
07120 LET E9=1-E9
07130 GO TO 07230
07140 REM  CALCULATE COLLISION EFFICIENCY DUE TO STOKES FLOW
07150 LET RO=D2*ABS(V6-V(J))/F2
07160 LET SO=R1*D2*D2*ABS(V(I)-V(J))/(1E.*E2*R2*D1)
07170 IF SO=0 THEN 07200
07180 LET RO=1./(1. +(1.2615 +.04571*RO^(.7818))*EXP(-2.9*LGT(SO)))
07190 GO TO 07220
07200 REM
07210 LET RO=1.
07220 REM
07230 FNE=E9
07240 FNEND
07250 END
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16. Abstract (Limit: 200 words)

The mist flow open-cycle OTEC concept proposed by S. L. Ridgway has much promise, but the fluid mechanics of the mist flow are not well understood. The creation of the mist and the possibility of droplet growth leading to rainout (when the vapor can no longer support the mist) are particularly troublesome. This report summarizes preliminary results of a numerical analysis initiated at SERI in FY79 to study the mist-lift process. The analysis emphasizes the mass transfer and fluid mechanics of the steady-state mist flow and is based on one-dimensional models of the mist flow developed for SERI by Graham Wallis. One of Wallis's models describes a mist composed of a single size of drops and another considers several drop sizes. The latter model, further developed at SERI, considers a changing spectrum of discrete drop sizes and incorporates the mathematics describing collisions and growth of the droplets by coalescence. The analysis results show that under conditions leading to maximum lift in the single-drop-size model, the multigroup model predicts significantly reduced lift because of the growth of droplets by coalescence. The predicted lift height is sensitive to variations in the mass flow rate and inlet pressure. Inclusion of a coasting section, in which the drops would rise ballistically without change in temperature, may lead to increased lift within the existing range of operation.

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