APPENDIX B Estimation of the magnitude of radiant heat exchange

Part of the radiant energy being transmitted between adjacent wet surfaces is absorbed by the non-luminous medium through which it is being transmitted, namely, the moist air. This absorption comes about because of the water vapour present in the air.

The water surfaces would have an emissivity of 0,96 and may be considered as black bodies. The moist air has an equivalent emissivity which is dependent on the water vapour pressure, the total pressure, the temperature and the mean beam path length of the radiation. The moist air emissivity may be estimated from information presented in a number of texts[49,72,73], the basis of which is summarized in Figure B.1.

Three different geometries of direct-contact heat exchanger are considered. First, a fluted type cooling tower packing with a characteristic dimension of 20 mm (the wetted air passages may be considered as small ducts which change direction every 300 mm in a zigzag pattern; see Chapter 4). Second, parallel corrugated sheets spaced at 100 mm (this is a simple film-type packing with a large spacing). Third, an open spray chamber. These three configurations were chosen in an attempt to cover the widest range of possibilities.

The radiation interchange between the water surfaces and the moist air is given by:

$$\dot{q}_r = \sigma \epsilon_a (T_{ws}^4 - T_a^4) \qquad (B.1)$$

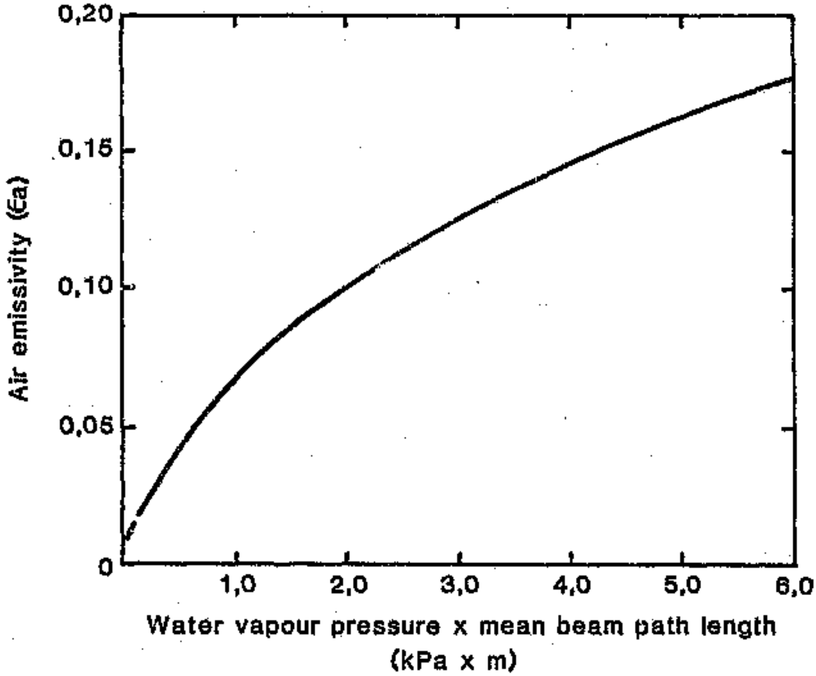


Figure B.1 Emmisivity of air due to water vapour, valid for temperatures from 0 to 50 °C which can be simplified[29] to:

$$\dot{q}''_r = h_r \left(t_{ws} - t_{db} \right) \tag{B.2}$$

where $h_r = 2{,}3 \times 10^{-7} \left(273 + t_{ave} \right)^3 \epsilon_a$ (B.3)

or $h_r = ($ [illegible] $_a$ for $t_{ave} = 25\,^{\circ}C$ (B.4)

The form of Equation B.2 is identical to the normal convective heat transfer equation and the value of the radiative heat transfer coefficient, h_r, may be compared directly to the normal convective film coefficient, h_c. The values of these coefficients for the three configurations being considered have been calculated and are given in Table B.1.

The ratios of the radiative to convective heat transfer coefficient have values of 0,3; 2,8; and 0,4 per cent for the three different situations. The value of 2,8 per cent applies to the parallel corrugated plates; in fact, this configuration was chosen as an example in an attempt to maximize this ratio.

It may be stated that the value of this ratio will always be less than 3 per cent but normally around 0,5 per cent. Thus, the radiant transfer is small when compared to the convective heat transfer, which itself is usually small when compared to the total heat transfer.

Table B.1 Comparison of the convective and radiative heat transfer coefficients

		Flute type packing 20 mm Spacing	Corrugated sheets film type packing 100 mm Spacing	Open spray chamber
Water vapour partial pressure	(kPa) (a)	3,2	3,2	3,2
Mean beam path length	(m)	0,015 (b)	0,19 (c)	1,8 (d)
Moist air emissivity		0,01 (e)	0,05	0.
Radiative heat transfer coefficient	(W/m² °C) (f)	0,06	0,31	1,20
Convective heat transfer coefficient	(W/m² °C)	20 (g)	11 (h)	300 (i)
Ratio h_r/h_c	(%)	0,3	2,8	0,4

Notes for Table B.1:

a. For an air condition of 25 °C (saturated) and a barometric pressure of 100 kPa.
b. Taken as 0,6 x diameter (see Mc Adams[49]).
c. Taken as 1,9 x distance between planes (see Mc Adams[49]).
d. Situation has been approximated to a spherical gas shape (see Bluhm[22]).
e. Value has been extrapolated from published data (see Mc Adams[49]).
f. Calculated at an average temperature of the air and the water surfaces of 25 °C. The value should be increased by 27 per cent or decreased by 23 per cent if the average temperature is 50 °C or 0 °C respectively.
g. Approximated to flow inside pipes with 3 m/s air velocity (see Mc Adams[49]).
h. Calculated for air velocity of 3 m/s and equivalent diameter of corrugations of 200 mm.
i. Surprisingly high value due to the high relative velocity between the drop and the air stream (see Bluhm[22]).

APPENDIX C Listing of computer program used to simulate the performance of counterflow direct-contact water-air heat exchanger

```
10          ! ***************************************************************
20          !
30          ! SIMULATOR FOR DIRECT CONTACT COUNTERFLOW WATER-AIR HEAT EXCHANGER
31          !
33          ! ###############################################################
40          ! This listing has been stripped of all input/output and iteration
              statements
50          !
60          !
70          !
90 Start:   ! Main loop starts here
100         !
110         !
120         ! +++++++++++++++++++++++++++++++ +++++++++++++++++++++++++++++++
130         ! Loop to calculate Tw_out and Mw_out from a knowledge of inlet air
              and water conditions and flow rates
140         !
150         ! ///////////////////////////////////////////////////////////////
160         ! Loop over N strips of tower
170         !
180         Pressure=Pressure_inlet-(I-1)/N*Delta_pressure  ! Pressure at
                                                            each strip
190         GOSUB Spalding  !Calculate Dmw(mass transfer),Delta_q(heat transfer)
                            per strip
200         Ash_out=Ash_in+Dmw/Ma  !apparent specific humidity, W, at outlet of
            strip kg/kg
210         Enthalpy_out=Q_tot/Ma+Enthalpy_in  ! Enthalpy at outlet of strip
220         Tdb_out=(Enthalpy_out-Ash_out*2501)/(1.005+Ash_out*1.84)    ! Dry-
                                                         bulb at outlet of strip
230         !
240         ! Test for fogging
250         ! Calculate W(sat) at Tdb_out and compare with  W_out
260         !
270         Esat=FNEsat(Tdb_out)
280         Ash_sat=.622*Esat/(Pressure-Esat)
290         IF Mfog>0 THEN 310
300         IF Ash_out<=Ash_sat THEN 600
310         Tdb_sat=Tdb_out   !First guess for Tdb_out if saturated
320         E=Ash_out*Pressure/(.622+Ash_out)       !Vapour pressure if no fog
330         E1=Ash_out     !First guess for saturated W at Tdb_sat
340         First_func=Ma*Enthalpy_in+Q_tot   !****
350         !
360         ! \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
370         ! Loop for correct Twb,Tdb if fogging occurrs
380         !
390         E8=.6105*EXP(17.27*Tdb_sat/(237.3+Tdb_sat))   !Saturated vapour
                                                        pressure at Tdb_sat
400         E8dash=E8*237.3*17.27/(237.3+Tdb_sat)^2
410         A7=.622*E8/(Pressure-E8)   !Saturated W at Tdb_sat
420         H7=1.005*Tdb_sat+(2501+1.84*Tdb_sat)*A7  !Guess for Enthalpy_out
                                                     if fogging occurrs
430         Sec_func=Ma*H7+(Mfog+Dmw+Ma*(Ash_in-A7))*4.187*Tdb_sat
440         Sec_func=Sec_func-Mfog*4.187*Tdb_in
450         Dash_7=.622*Pressure*E8dash/(Pressure-E8)^2
460         F=Sec_func-First_func
470         Fdash=Ma*(1.005+(2501+1.84*Tdb_sat)*Dash_7+1.84*Ash)
480         Fdash=Fdash+(Mfog+Dmw+Ma*(Ash_in-A7))*4.187-Ma*4.187*Dash_7*Tdb_sat
490         IF ABS(F/Fdash)<1E-8 THEN 530
500         Z3=F/Fdash
```

```
510         Tdb_sat=Tdb_sat-23  !Tdb_out if saturated
520         GOTO 390
530         D_mfog=Dmw*Ma*(Ash_in-A7)
540         Mfog=Mfog+D_mfog               !Mass of water vapour due to fogging
550         Tdb_out=Tdb_sat
560         Twb_out=Tdb_out
570         Ash_out=A7
580         Enthalpy_out=H7
590         GOTO Ok
600         !
610         ! End of loop for fogging
620         ! \\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\\
630         GOSUB Wet_bulb    !Calculates Twb_out if no fogging
640 Ok:     Sigma_out=Enthalpy_out-Ash_out*Cw*Twb_out
650         New_tw=(Cw*Mw*Tw(I)+Q_tot)/((Mw+Dmw)*Cw)
660         Delta_tw=New_tw-Tw(I+1)
670         Tw(I+1)=New_tw
680         Mw_n=Mw+Dmw           !Water flow in next strip is actually INLET
                                    water flow rate to this strip
690         ! Prepare for next strip
700         Tdb_in=Tdb_out
710         Twb_in=Twb_out
720         Ash_in=Ash_out
730         Enthalpy_in=Enthalpy_out
740         Sigma_in=Sigma_out
750         Q_tower=Q_tower+Q_tot!
760         Sum_sens=Sum_sens+Q_sens               !Sum of sensible heat
770         Lat=Lambda*Dmw                         !Latent heat
780         Sum_lat=Sum_lat+Lat
790         Sum_fog=Sum_fog+Lambda*D_mfog          !Sum of heat due to fogging
800         !
810         !  F - n  loop over N strips
820         !         ///////////////////////////////////////////////////////
830         M               !Return Mfog to air stream
840         T           Mfog)*Tw(I)-Mfog*Tdb_out)/Mw
850         Q     r=Q_tower-Mfog*Cw*Tdb_out
860         IF (ABS(Tw(I)-Twi)<.0005) AND (ABS(Mwi-Mw)<.00005) THEN Print_result
s                                                ! 0.005% error for flow
870         Tw_error=Twi-Tw(I)        !Error in water temperature
880         Mw_error=Mwi-Mw        !Error in water flow rate
890         Two_guess=Two_guess+Tw_error*Error_factor !New guess for Two
900         Mwo=Mwo+Mw_error        !New guess for Mwo
910         !
920         ! End of loop for Tw_out and Mw_out
930         ! ++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
940         !
950         ! End of main program
960         ! ##############################################################
970         !
980         ! **************************************************************
990         !
1000  STOP
```

```
1010        ! ********************************************************************
1020  !
1030 Spalding:! Calculates water properties by method of Spalding
1040  !
1050        X=1    !For water temps ie need INLET temp for this strip
1060        Tfilm=(Tw(X)+Tdb_in)/2   !Temperature of film
1070        Ews=.6105*EXP(17.27*Tw(X)/(237.3+Tw(X)))        !Saturated vapour
                                                      pressure of water surface
1080        Esatd=.6105*EXP(17.27*Twb_in/(237.3+Twb_in))        !Saturated vapour
                                                              pressure at wet bulb
1090        Eair=FNE(Twb_in,Tdb_in,Pressure)  !Vapour pressure of air
1100        Efilm=.6105*EXP(17.27*Tfilm/(237.3+Tfilm))      !Saturated vapour
                                                 pressure at film temperature
1110        Ash_film=.622*Efilm/(Pressure-Efilm)  !apparent specific humidity, W
1120        Ash_ws=.622*Ews/(Pressure-Ews)
1130        Sigma_ws=1.005*Tw(X)+(2501-2.387*Tw(X))*Ash_ws       !Sigma heat water
                                                 surface
1140        Mh2o_ws=.622*Ews/(Pressure-.378*Ews) ! IN Kg H2O/Kg VAIR  TSHws
1150        Mh2o_inf=.622*Eair/(Pressure-.378*Eair) ! IN Kg H2O/Kg VAIR TSHinf
1160        Lambda=2501-2.387*Tw(X)              !kJ/kg  Latent heat
1170        Cp=(1.005+1.84*Ash_film)*(Pressure-Efilm)/(Pressure-.378*Efilm)
                                                     ! IN kJ/Kg C    Film Cp
1180        K=(2405+7.788*Tfilm)*10^(-5)      !Film conductivity
1190        Diffusivity=1.676*10^(-7)*(Tfilm+273.15)^1.694/Pressure
                                                 ! m^2/SEC  Film diffusivity
1200        Ro_film=(Pressure-.378*Efilm)/(.287045*(273.15+Tfilm))   !kg vair/m^3
1210        Lewis=(Cp*1000*Ro_film*Diffusivity/K)^(2/3)   !Lewis no
1220        B=LOG((1-Mh2o_inf)/(1-Mh2o_ws))     !Mass transfer driving force
1230        Dmw=Hc_a/N*Lewis*B/Cp       !Mass trans kg/s
1240        Q_sens=Hc_a/N*(Tw(X)-Tdb_in)    !Sensible heat added
1250        Q_tot=Q_sens+Lambda*Dmw         !Total heat added
1260    RETURN
1270        ! ****************************************************************
1280        !
1290 Wet_bulb:! Calculates Twb_n_1 from Ash_n_1
1300        !
1310        Twb_guess=Twb_in
1320         E=FNE(Twb_guess,Tdb_out,Pressure)
1330         F=-.622*E
1340         F=Ash_out+F/(Pressure-E)
1350         Fdash=-.622*FNDe(Twb_guess,Tdb_out,Pressure)*Pressure
1360         Fdash=Fdash/(Pressure-E)^2
1370         Twb_out=Twb_guess-F/Fdash
1380         IF ABS(F/Fdash)<1.0E-4 THEN 1410
1390         Twb_guess=Twb_out
1400         GOTO 1320
1410      RETURN
1420        !
1430        ! ****************************************************************
1440        !
1450 DEF FNE(W,D,P)                   ! Vapour pressure  kPa
1460        Esat=.6105*EXP(17.27*W/(237.3+W))
1470        E=(Esat*(1555.6-2.465*W+1.005*D)-P*(.005*(D-W))/(1555.6+.139*D-1.599*W
-Esat*.14*(D-W)/P)
1480         RETURN E
1490     FNEND
1500        !
```

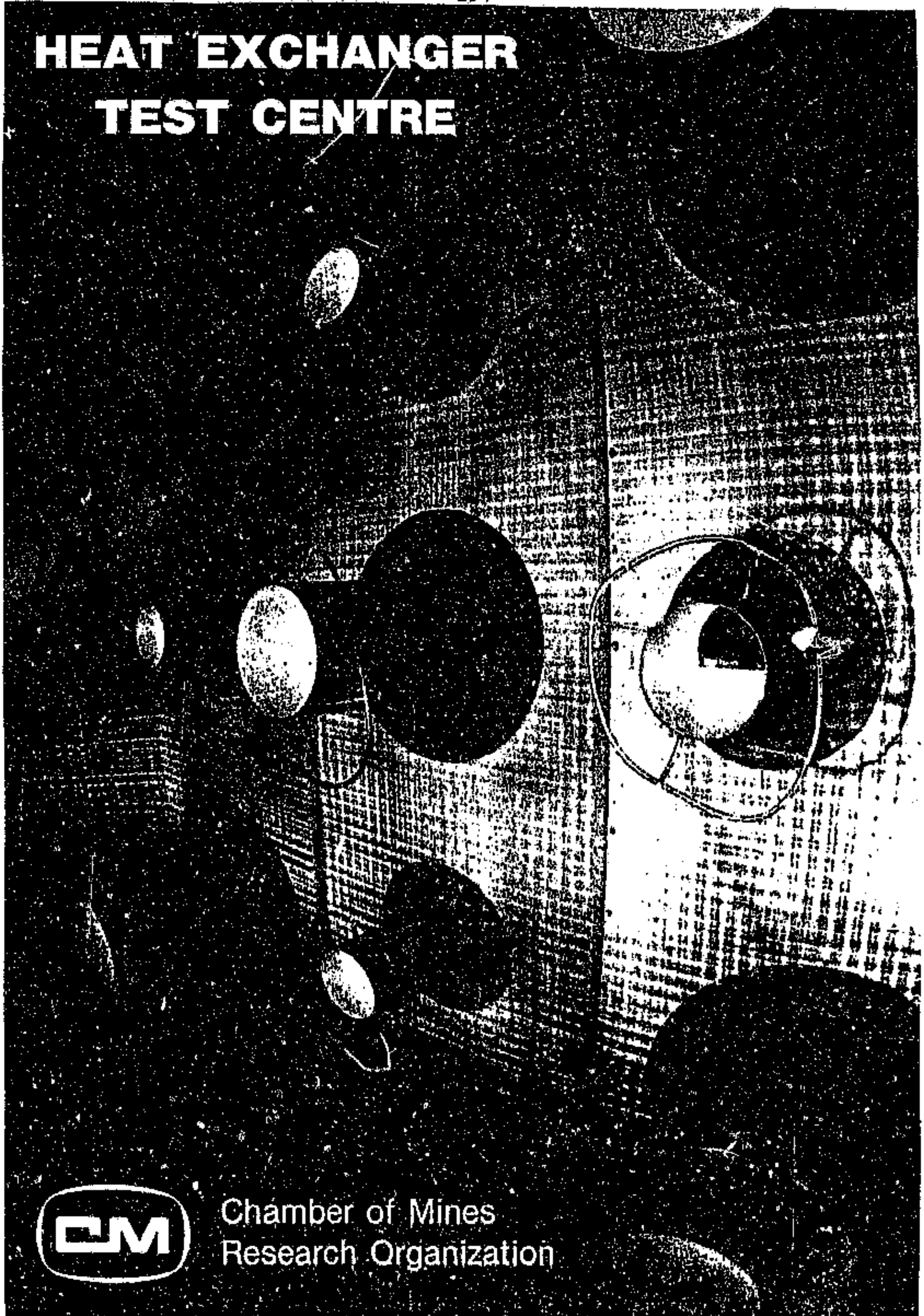
```
1510      ! *******************************************************************
1520      !
1530 DEF FNEsat(W)                       ! Saturated vapour pressure   kPa
1540      Esat=.6105*EXP(17.27*W/(237.3+W))
1550      RETURN Esat
1560    FNEND
1570      !
1580      ! *******************************************************************
1590      !
1600 DEF FNDe(W,D,P)                     ! First derivative of vapour pressure
1610      Esat=.6105*EXP(17.27*W/(237.3+W))
1620      De=(371.4+.04*D-.4*W)*(Esat*-.6+(371.4+.24*D-.6*W)*FNDesat(W)+.24*P)+(
Esat*(371.4+.24*D-.6*W)-.24*(D-W)*P)*.4
1630      De=De/(371.4+.04*D-.4*W)^2
1640      RETURN De
1650    FNEND
1660      !
1670      ! *******************************************************************
1680      !
1690 DEF FNDesat(W)                      ! First derivative of saturated vapour
                                           pressure
1700      Desat=.6105*(((237.3+W)*17.27-17.27*W)/(237.3+W)^2)
1710      Desat=Desat*EXP(17.27*W/(237.3+W))
1720      RETURN Desat
1730    FNEND
1740      !
1750      ! *******************************************************************
```

APPENDIX D. Heat exchanger test facility

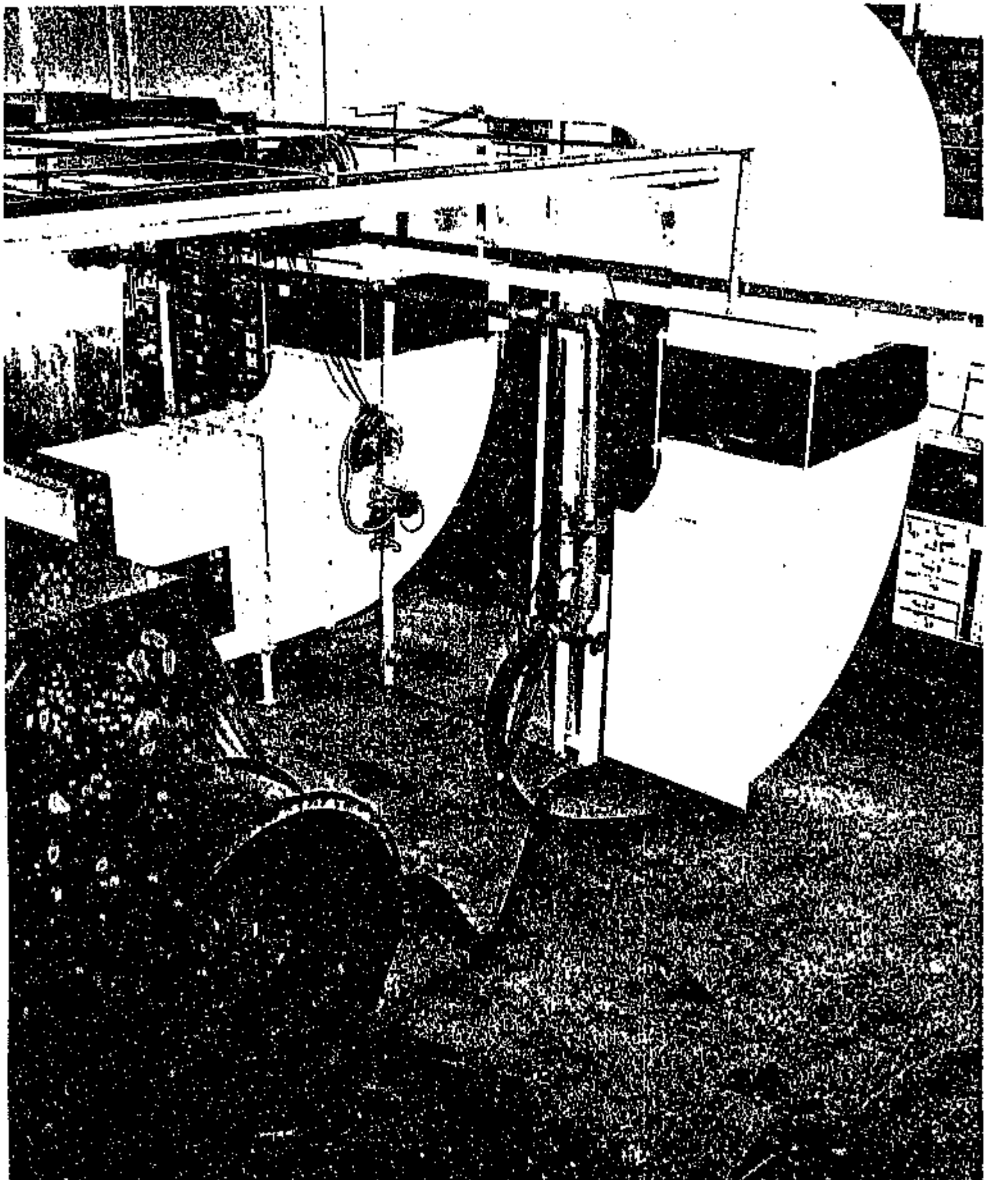
This appendix presents a published brochure giving details of the test facility.

(In support of this thesis it is noted that the author was responsible for the design, erection, commissioning of the centre as well as the present extensive programme of research carried out at this facility[3]).

HEAT EXCHANGER TEST CENTRE



Chamber of Mines Research Organization



Interior of test hall

Front cover — Nozzle bank for measuring airflow

THE NEW HEAT EXCHANGER TEST CENTRE

The commissioning of the Heat Exchanger Test Centre of the Chamber of Mines of South Africa Research Organization has provided the South African mining industry with an important research and testing centre. It is unique in that it is the largest facility of its kind designed specifically to provide simulated underground environmental conditions for the testing of heat transfer equipment.

The effective distribution of refrigeration to underground workings is indispensable for safe and profitable gold mining. The installed refrigeration capacity in the South African gold mines in 1983 was approximately 800 MW(R) and more than 75 per cent of this refrigeration is distributed to heat exchangers of various types, in which chilled water is used to cool the ventilation air.

To mines these heat exchangers represent a considerable investment, in terms of both capital and running costs. Continuing research is thus needed to ensure that the varying, increasingly-stringent demands of the industry can be satisfied for cost-effective equipment for conditioning the underground environment.

THE NEED FOR A HEAT EXCHANGER TEST CENTRE

It is essential that research and development on heat exchangers be carried out under the thermal conditions in which they are to operate. Up until now the Research Organization has had to conduct most of the testing underground in mine workings, whenever and wherever suitable locations could be found. The bulk of this research could however be done more quickly and cost effectively in a surface test facility capable of simulating the underground environment. No such facility has previously been available.

The advantages of a surface test centre include:

- the important variables such as air and water flow rates, temperatures, and air humidity can be varied and controlled more conveniently than is possible in mine sites;
- the sophisticated measuring and data processing equipment required for the test programmes does not have to be protected from the rigours of the underground environment;
- heat exchangers to be evaluated can be installed and tested rapidly; and
- the test data can be processed and evaluated almost immediately.

The Heat Exchanger Test Centre will greatly facilitate preliminary and routine testing, as well as fundamental studies on heat and mass transfer, under controlled conditions. This facility will, however, not replace underground evaluation, which will always ultimately be required to confirm the laboratory results and ascertain whether the equipment can operate satisfactorily under actual mining conditions. In addition new types of heat exchangers can be evaluated for the industry.

TECHNICAL DESCRIPTION

The Centre is housed in one of the main buildings at the Carlow Road complex of the Research Organization, and forms part of the Environmental Engineering Laboratory. The main sections are:

- **two test bays;**
- **a refrigeration installation;**
- **a water circuit; and**
- **an air circuit.**

Test bays

The test bays each occupy a floor area of 10 x 2,5 m. In these bays a supply of hot humid air (at temperatures similar to those found in deep gold mines) can be provided, as well as cold water at temperatures similar to those available from underground or surface mine refrigeration plants.

The refrigeration installation

A 230 kW(R) screw-compressor refrigeration machine, located near the test bays, is used to provide hot water from the condenser and the cold water from the evaporator. The whole system has been designed to conserve energy; the total electrical power consumption is less than 150 kW. The technical specifications of the system are:

Air flow rate	:	up to 12 m^3/s
Fan air pressure at design flow rate	:	up to 2 kPa
Water flow rate	:	up to 15 ℓ/s
Cooling duty	:	up to 230 kW
Heating duty	:	up to 300 kW
Water temperature (minimum)	:	4 °C
Air temperature (maximum)	:	30 °C (saturated)

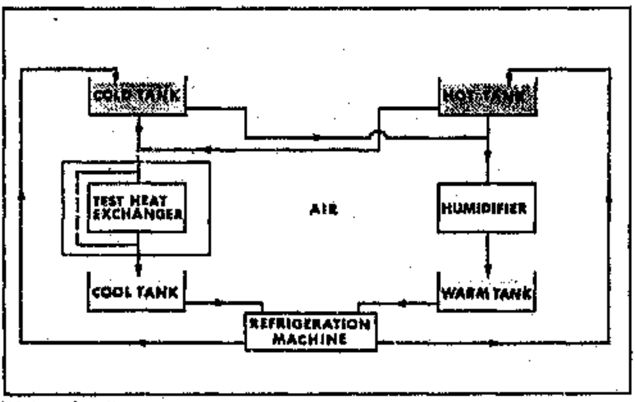
30 000 litre water tanks have been installed to store hot water (40 °C) and cold water (4 °C) so that heat transfer tests, at larger duties than those shown in the table, can be carried out for limited periods of time. A full-scale test of a 500 kW heat exchanger could typically be carried out for over an hour.

Water circuit

The water circuit provides chilled water, at a controlled temperature, to the heat exchangers under test in the bays. It consists of four water tanks storing cold, cool, warm and hot water respectively, with an interconnecting system of pipes and valves. The water consumption is kept to a minimum by recycling the water between the four tanks after cooling or heating.

Water is pumped from the cool water tank and chilled in the refrigeration plant to 4 °C, and is then stored in the cold water tank. Water from the warm water tank enters the condenser of the refrigeration plant and leaves at a temperature of 40 °C; this water is stored in the hot water tank. The temperature of the water pumped to the heat exchanger under test is controlled by mixing the water at 4 °C with that at 40 °C. The water from the heat exchangers in the test bays is returned to the cool water tank.

The duty of the humidifier is controlled by varying the temperature of the water entering it. This is achieved by adjusting the proportions of feed water from the cold and hot water tanks. The return water from the humidifier is pumped to the warm water tank. A cooling tower has been installed above the warm water tank to allow surplus heat to be rejected to the atmosphere when necessary.



Water circuit

Air circuit

The air circuit provides the test bays with a flow of air at the temperature and humidity needed to simulate the underground environmental conditions selected for the test.

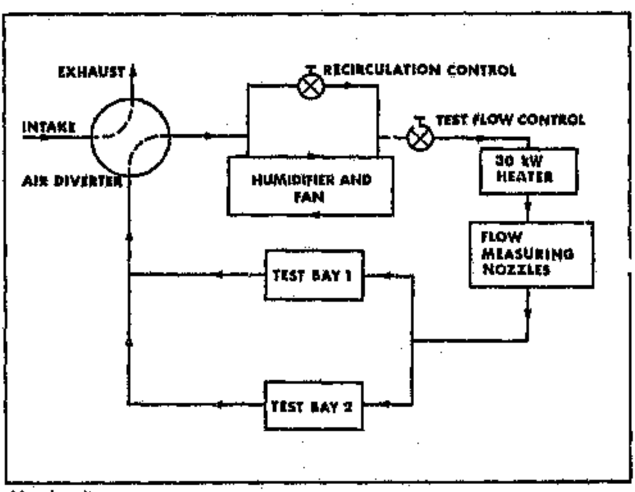
Air is drawn by a centrifugal fan through the humidifier where it is heated and humidified. The airflow is then divided, with some air flowing to the heat exchanger test bays and the balance by-passed back to the humidifier. This by-pass arrangement ensures that the fan operates near to its design conditions even though the air flow through the test section may vary between 1 m³/s and 12 m³/s. Ambient air can also be introduced into the air circuit to extend the range of test conditions.

The gap between the wet-bulb and dry-bulb temperatures of the air being fed to the test bays may be controlled by a 30 kW electrical heater.

The air from the humidifier is passed into a measuring section fitted with a set of nine nozzles designed to an ASHRAE standard. By selecting various combinations of the test nozzles, flow rates between 0,5 m³/s and 12 m³/s can be measured accurately.

The air is then directed to one of the two test bays before returning to the humidifier for re-heating and humidifying.

The energy requirement is minimized by operating in a closed circuit. The energy supply needed to increase the wet-bulb temperature of 12 m³/s of air from 5 °C to 30 °C would be over 1 000 kW in a once-through system but, by using a closed loop, this has been reduced to 230 kW.



Air circuit

THE USES OF THE HEAT EXCHANGER TEST CENTRE

The Research Organization is currently devoting considerable attention to devising methods for reducing the heat and pollutant load on the underground environment, and to improving methods for conditioning this environment. This includes the following types of investigations.

Fundamental work on heat and mass transfer

Research in this area will give a better understanding of the heat and mass transfer processes which take place at near-saturation conditions, similar to those found in deep mines.

Heat transfer and pressure drop characteristics of the various cooling coils

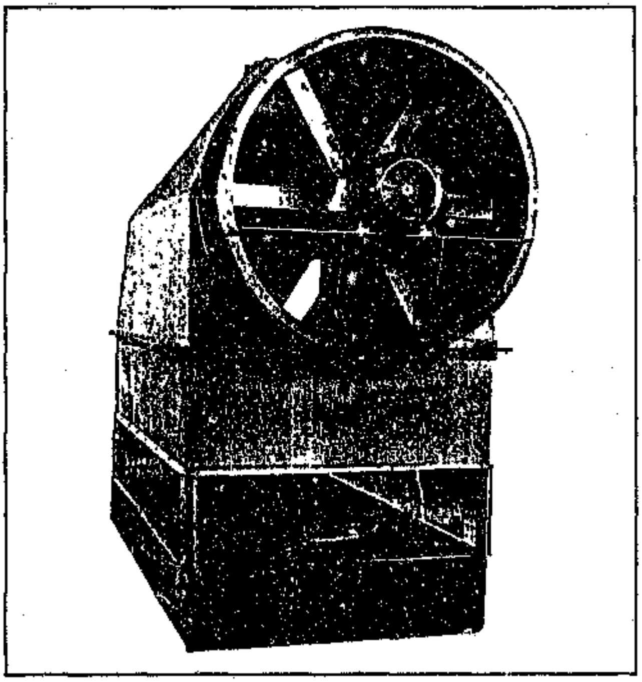
A knowledge of these characteristics is necessary to design both improved cooling coils and improved water distribution systems, and to determine the optimum operating conditions of these heat exchangers. Investigations will also be carried out into the effect of air flow distribution on cooling coil performance. It is generally recognized that fouling is one of the major problems associated with cooling coil performance, and its effect will be evaluated together with methods of cleaning the coils while in service.

Development of dust filtration equipment

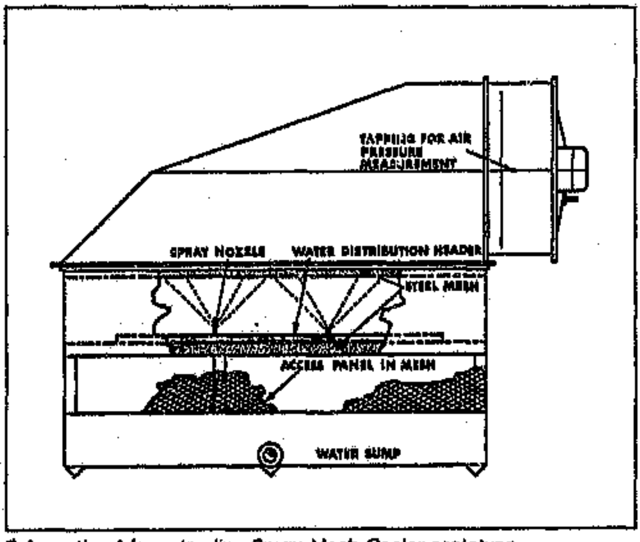
Water spray chambers provide a method of filtering large volumes of ventilation air underground with minimal energy expenditure. The performance characteristics of various spray nozzles and the effect of water spray pressure on the filtering efficiency are being studied.

Development of spray air coolers

Direct-contact air coolers are more suitable for some situations than cooling coils and heat exchangers using spray systems with and without packing are presently being studied.



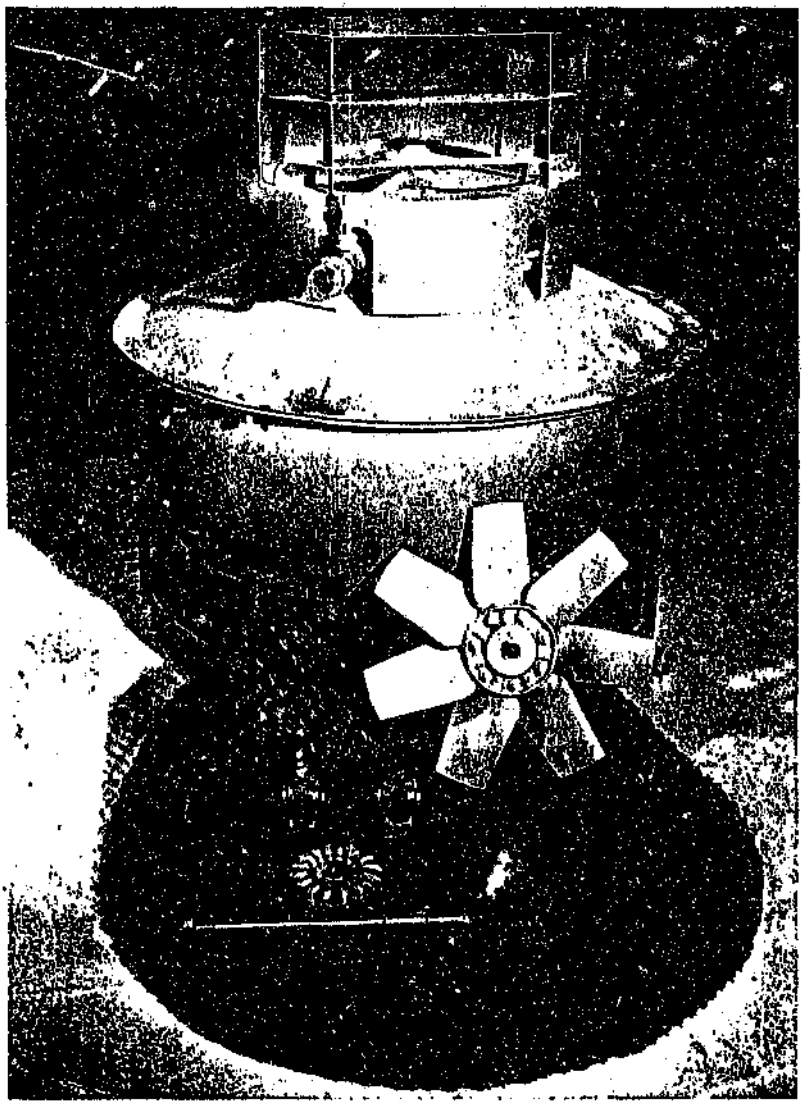
Free-standing Spray Mesh Cooler prototype designed for a nominal duty of 500 kW, a water flow of 7,5 ℓ/s and an air flow of 10 m³/s. The unit is 2,8 m long x 1,4 m wide x 2,5 m high.



Schematic of free-standing Spray Mesh Cooler prototype

Development of stope air coolers

A programme to develop heat exchangers which may be used to provide *in situ* cooling in narrow stopes has commenced. These heat exchangers use the water pressure (by means of turbines) to create the air flow and thus obviate the need for a supply of electrical power.



A one metre diameter stope air cooler designed for a water supply pressure of 400 kPa, a water flow of 1,8 ℓ/s and a nominal cooling duty of 30 kW. The air flow of 1,2 m³/s is induced by a 480 mm diameter fan driven by a 100 mm diameter Pelton wheel. Fan, fan shaft, Pelton wheel and bearing housings are shown together with a sample of plastic mesh heat exchanger packing.

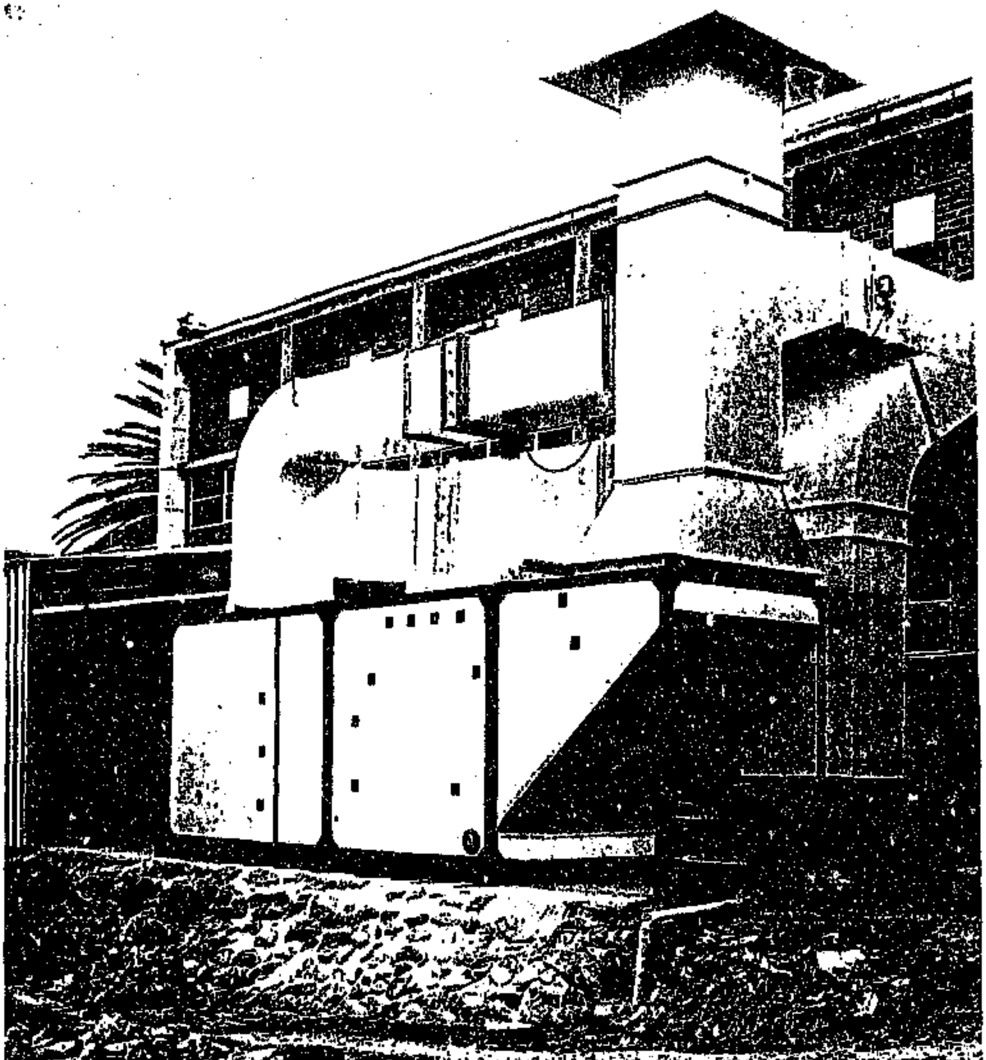
TECHNICAL ASSISTANCE

The Heat Exchanger Test Centre will augment the service provided by the Research Organization to the mining industry in testing the performance of new types of heat exchangers.

For further information please contact:
The Director,
Environmental Engineering Laboratory,
Research Organization,
Chamber of Mines of South Africa.
P.O. Box 809,
Johannesburg, 2000.

Telephone 726-3020,
Telex 4-26070 SA.

Chamber of Mines of South Africa
Research Organization



Exterior view showing air humidifier, ducting and refrigeration plant room.

APPENDIX E Specification of spray nozzles used in test tower

The test tower made use of four nozzles spraying downwards with each nozzle producing a square water distribution pattern. The nozzles used were Spraying Systems Co. type 1½H230 SQ; specifications are given below:

CATALOG 25

SPRAYING SYSTEMS CO.

INDUSTRIAL

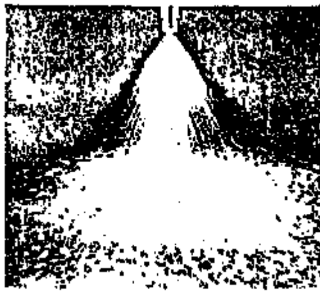
SPRAY NOZZLES

AND ACCESSORIES

SPRAYING SYSTEMS CO.

Engineers and Manufacturers
3201 Randolph Street • Bellwood, Illinois 60104
Telephone: AREA CODE 312 Linden 4-0380 • Cable Address: SPRAYSYSCO

FullJet NOZZLES
square spray



Spray Characteristics—Square spray pattern with good distribution throughout square pattern. Good atomization at all pressures.

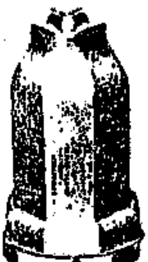
Construction—Nozzles made with removable, internal offset vanes. Types G and GG have replaceable caps.

Materials—Supplied standard in brass, steel and types 303 and 316 stainless steel (cast stainless steel type H-SQ in type 316 only). Other materials available on special order.

Square Spray Pattern

Type HH-SQ
male connection

Type GG-SQ
with removable cap
male connection



Type H SQ
cast type
one piece body
female connection

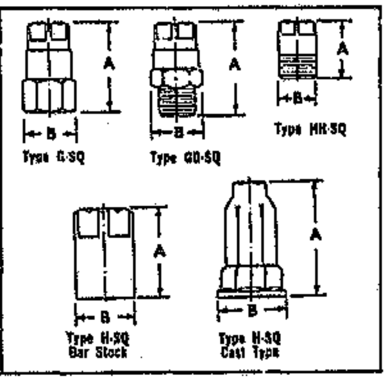
See pages 58 to 63 for spray nozzle accessories.

Nozzle No.		Pipe Conn NPT	Orifice Diam.	Max. Free Passage Diam*	CAPACITY GPM (gallons per minute) at p.s.i. (pounds per square inch)										SPRAY ANGLE		
Female Pipe Conn.	Male Pipe Conn.				5 p.s.i.	7 p.s.i.	10 p.s.i.	20 p.s.i.	30 p.s.i.	40 p.s.i.	60 p.s.i.	80 p.s.i.	100 p.s.i.	150 p.s.i.	7 p.s.i.	20 p.s.i.	80 p.s.i.
1/4G3.6 SQ.	1/4GG3.6 SQ.	1/4"	5/64"	.050"	.26	.31	.36	.50	.60	.69	.83	.95	1.1	1.3	40°	52°	47°
1/4G5 SQ.	1/4GG5 SQ.	1/4"	3/32"	.050"	.43	.51	.60	.83	1.0	1.1	1.4	1.6	1.8	2.1	60°	66°	60°
1/4G10 SQ.	1/4GG10 SQ.	1/4"	9/64"	1/16"	.72	.85	1.0	1.4	1.7	1.9	2.3	2.6	2.9	3.9	62°	67°	61°
1/4G12 SQ.	1/4GG12 SQ.	1/4"	1/8"	1/16"	.86	1.0	1.2	1.7	2.0	2.3	2.8	3.2	3.5	4.3	70°	75°	68°
3/8G18 SQ.	3/8GG18 SQ.	3/8"	9/64"	3/32"	1.3	1.5	1.8	2.5	3.0	3.4	4.1	4.7	5.3	6.4	71°	75°	68°
1/2G29 SQ.	1/2GG29 SQ.	1/2"	7/32"	1/8"	2.1	2.5	2.9	4.0	4.8	5.5	6.7	7.6	8.5	10.0	71°	75°	68°
. . . .	1/8HH3.6 SQ.	1/8"	5/64"	.050"	.26	.31	.36	.50	.60	.69	.83	.95	1.1	1.3	40°	52°	47°
. . . .	1/8HH4.8 SQ.	1/8"	5/64"	.050"	.34	.40	.48	.66	.80	.91	1.1	1.3	1.4	1.7	48°	63°	57°
. . . .	1/8HH6 SQ.	1/8"	3/32"	.050"	.43	.51	.60	.83	1.0	1.1	1.4	1.6	1.8	2.1	62°	71°	65°
. . . .	1/8HH10 SQ.	1/8"	9/64"	1/16"	.72	.85	1.0	1.4	1.7	1.9	2.3	2.6	2.9	3.5	62°	67°	61°
. . . .	1/8HH12 SQ.	1/8"	1/8"	1/16"	.86	1.0	1.2	1.7	2.0	2.3	2.8	3.2	3.5	4.3	70°	75°	68°
. . . .	1/4HH14.5 SQ.	1/4"	.154"	3/32"	1.1	1.2	1.45	2.0	2.4	2.8	3.3	3.8	4.2	5.1	78°	82°	75°
. . . .	3/8HH18 SQ.	3/8"	5/32"	3/32"	1.3	1.5	1.8	2.5	3.0	3.4	4.1	4.7	5.3	6.4	71°	75°	68°
. . . .	1/2HH29 SQ.	1/2"	7/32"	1/8"	2.1	2.5	2.9	4.0	4.8	5.5	6.7	7.6	8.5	10.0	71°	75°	68°
. . . .	1/2HH36 SQ.	1/2"	1/4"	.1"	2.6	3.1	3.6	5.0	6.0	6.9	8.3	9.5	10.5	13.0	78°	82°	75°
. . . .	3/4H 150 SQ.	3/4"	19/64"	11/64"	3.7	4.3	5.0	7.0	8.4	9.6	11.5	13.2	14.6	17.6	71°	75°	68°
1H106 SQ.	. . . .	1"	25/64"	5/32"	7.6	8.9	10.6	14.5	17.5	20	24	28	31	37	78°	80°	73°
1¼H177 SQ.	. . . .	1¼"	1/2"	3/8"	12.6	15.0	17.7	25	30	34	41	47	52	63	78°	80°	73°
1½H230 SQ.	. . . .	1½"	9/16"	11/32"	16.6	13.5	23	32	39	44	53	61	67	80	73°	77°	70°
2H290 SQ.	. . . .	2"	39/64"	5/16"	21	25	29	40	48	55	67	78	85	100	66°	70°	64°
2H360 SQ.	. . . .	2"	11/16"	3/16"	26	31	36	50	60	69	83	95	105	130	70°	74°	67°
2H480 SQ.	. . . .	2"	49/64"	5/16"	34	40	48	66	80	91	110	125	138	166	79°	82°	74°
2½H490 SQ.	. . . .	2½"	51/64"	5/16"	35	41	49	67	81	92	113	126	142	170	62°	67°	61°
2½H590 SQ.	. . . .	2½"	7/8"	9/16"	43	50	59	81	99	113	136	155	173	208	75°	78°	71°

*Foreign matter with maximum diameter as listed can pass through nozzle without clogging.

DIMENSIONS AND WEIGHTS

Nozzle No.	Net Weight	A	B
1/8G-SQ.	1 oz.	1½"	9/16" Hex.
1/4G-SQ.	2 oz.	1 11/32"	11/16" Hex.
3/8G-SQ.	3 oz.	1 17/32"	13/16" Hex.
1/2G-SQ.	5 oz.	1 25/32"	1" Hex.
1/8GG SQ.	1 oz.	1 5/16"	9/16" Hex.
1/4GG SQ.	2 oz.	1 7/16"	11/16" Hex.
3/8GG SQ.	3 oz.	1 9/16"	13/16" Hex.
1/2GG-SQ.	5 oz.	1 13/16"	1" Hex.
1/8 HH SQ.	1/2 oz.	3/4"	1/2" Diam.
1/4HH SQ.	1 oz.	3/4"	19/32" Diam.
3/8HH-SQ.	1 oz.	15/16"	25/32" Diam.
1/2HH-SQ.	2 oz.	1 5/16"	1 1/16" Diam.
3/4HH-SQ.	5 oz.	1 25/32"	1 5/16" Diam.
1H SQ.	12 oz.	2 11/16"	1½" Diam.
1¼H SQ.	1 lb.	3½"	1⅞" Diam.
1½H SQ.	1½ lb.	4"	2 3/16" Diam.
2H-SQ.	2½ lb.	5"	3" Diam.
2½H-SQ.	4½ lb.	6 11/32"	3 7/16" Diam.



Patent Nos. 2,305,210
and 3,101,825

FullJet® NOZZLES wide angle square spray

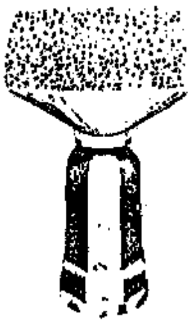
Spray Characteristics—Full square spray pattern combined with an unusually wide spray angle to provide maximum surface area coverage per nozzle. Distribution is uniform throughout the pattern cross section. Impact is low due to wide angle of spray.

Construction — Offered in a complete range of pipe sizes. Internal vanes are removable.

Materials — Standard in brass, iron or steel, and stainless steel. Other special materials can be supplied to order.

Recommended For—Multi-nozzle installations such as air and gas washers and scrubbers, liquor washers and web sprayers. Square spray patterns permit use of fewer nozzles per header to provide complete and uniform coverage of area sprayed.

Wide Angle Square Spray Pattern



Nozzle No.		Pipe Conn. Size NPT	Orifice Diam.	Maximum Free Passage Diam.*	CAPACITY GPM (gallons per minute) at p.s.i. (pounds per square inch)						SPRAY ANGLE		
Female Pipe Conn.	Male Pipe Conn.				5 p.s.i.	10 p.s.i.	20 p.s.i.	40 p.s.i.	60 p.s.i.	80 p.s.i.	5 p.s.i.	10 p.s.i.	80 p.s.i.
	1/4HH14WSQ	1/4"	9/64"	1/16"	1.0	1.4	1.9	2.6	3.1	3.5	99°	101°	93°
	3/8HH20WSQ	3/8"	11/64"	3/32"	1.5	2.0	2.7	3.6	4.4	5.0	104°	110°	94°
	1/2HH35WSQ	1/2"	15/64"	1/8"	2.6	3.5	4.9	6.7	8.2	9.3	104°	110°	102°
3/4H71WSQ	3/4HH71WSQ	3/4"	23/64"	11/64"	5.1	7.1	10	13.9	16.9	19.4	105°	110°	102°
1H130WSQ	1HH130WSQ	1"	31/64"	7/32"	8.8	13	18	25	31	35	107°	110°	107°
1 1/4H190WSQ		1 1/4"	39/64"	9/32"	13.8	19	27	37	45	52	108°	111°	109°
1 1/2H290WSQ		1 1/2"	31/32"	5/16"	20	29	40	55	66	76	109°	114°	109°
2H560WSQ		2"	41/64"	7/16"	40	56	79	110	135	154	110°	114°	109°
2 1/2H830WSQ		2 1/2"	1 1/4"	9/16"	59	83	117	164	200	230	110°	115°	109°
3H1070WSQ		3"	1 3/8"	11/16"	81	107	149	208	250	290	110°	115°	109°

* Foreign matter with maximum diameter as listed can pass through nozzle without clogging.

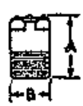
Type HH male connection

Patent No. 2,305,210 and Patents Pending

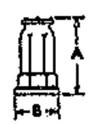
Type H (bar stock) female connection 3/4H and 1H

DIMENSIONS AND WEIGHTS

Type H female conn. (bar stock) nozzle numbers 3/4H and 1H



Type HH male conn. (bar stock) nozzle numbers 1/4HH through 1HH



Type H female conn. (casting) nozzle numbers 1 1/4H through 3H

Nozzle No.	A (length)	B (diameter)	Net Weight
1/4HH	29/32"	1 5/32"	1/2 oz.
3/8HH	1 3/16"	31/32"	1 oz.
1/2HH	1 7/32"	15/16"	1 1/2 oz.
3/4HH	1 15/32"	1 5/16"	3 oz.
1HH	2 1/32"	1 9/16"	7 oz.
3/4H	2 5/16"	1 3/8"	7 oz.
1H	2 23/32"	1 1/2"	11 oz.
1 1/4H	3 3/16"	2 1/16"	1 1/4 lbs.
1 1/2H	4 5/32"	2 5/16"	2 lbs.
2H	5 5/16"	3"	3 1/2 lbs.
2 1/2H	6 1/4"	3 9/16"	4 1/2 lbs.
3H	7 11/32"	4 1/8"	6 1/2 lbs.

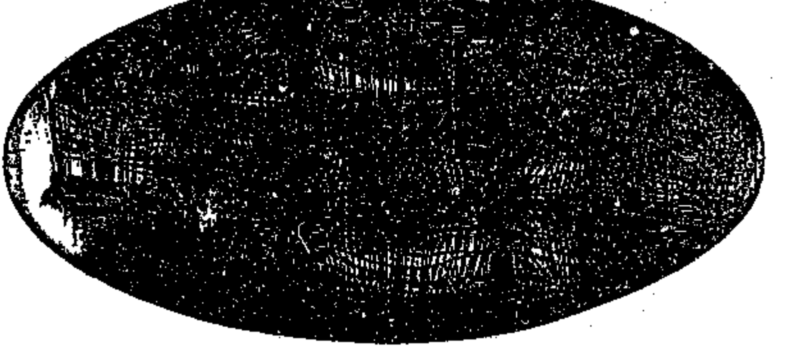
Type H cast type female connection 1 1/4H through 3H

See page 64 for spray coverage and pipe friction information.

APPENDIX F Specification of mist eliminator mesh used in test tower

The mist eliminator used in the test tower consisted of four layers of interlaced plastic mesh in the form of a mat. The design used was Kimre Inc type 16/96; specifications are given below:

B-Gon™ Mist Eliminator



B-Gon provides high efficiency removal of the liquid phase from the vapor phase, and low pressure drop through the material, allowing higher throughput at lower energy usage.

B-Gon achieves maximum impingement with lower drag because essentially all of its fibers are aligned perpendicular to the gas flow, rather than in the random arrangement common to knitted wire mesh materials. In addition, the B-Gon mist eliminator combines the best features of knitted wire and plate type eliminators. The ladder arrangement of the two sets of filaments causes a change in direction of vapor flow which aids in droplet removal by centrifugal action and also produces a cross flow of the removed water that flushes particulates from the media. The table below shows the efficiency of the B-Gon style 16/96 under test conditions.

Test Data—Style 16/96 (0.75" Thick)

Velocity Ft/Sec	ΔP Inches H_2O	Efficiency: % Drop Diameter, Microns 2-4	4-6	6-8	8-10	10-12	10-14
5.2	.42	98.73	99.49	99.82	99.96	99.99	99.99
8.2	1.08	99.30	99.56	99.79	99.92	99.96	99.99

The efficiency data, obtained by Calspan Corporation, is valid to the nearest 0.1%. The tests were done using water fogs in a saturated atmosphere.

Sizes and Filament Diameters

B-Gon mist eliminators are available in sizes up to 6 feet by 20 feet. In the great majority of applications, this size range eliminates the need for piecing. B-Gon mist eliminators are available in filament diameters from 4 mils to 62 mils, and various void fractions, which provide a wide range of physical characteristics for individual applications.

B-Gon is stock manufactured from either polypropylene or Kynar. (Kynar is the registered trademark for Pennwalt Corporation's polyvinylidene fluoride resin.)

Design Information and Examples

Efficiency - The amount of liquid passing through the eliminator without being captured may be expressed as

$$Pt = \exp(-K_f N) \quad \text{or} \quad K_f = \frac{-\ln(Pt)}{N}$$

The value of K_f is determined experimentally, or estimated from theory. Results for style 16/96 are shown in Figure 1.

Example - To achieve a desired 99.9% efficiency of removal at a gas velocity of 5 fps for 3 micron droplets one calculates

$$-\ln(Pt) = -\ln(1-0.999) = -\ln(0.001) = 6.93.$$

From Figure 1 for 16/96 at a velocity of 5 fps, K_f is found

$$K_f = 0.452 = \frac{-\ln(Pt)}{N} \quad N = 15.3 \text{ layers, use } 16.$$

Pressure Drop - Pressure drop through a mist eliminator can be related by

$$\Delta P = K_f \times V^2 \times N.$$

For style 16/96 with air at 760 mmHg and 75°F. at low liquid rates this expression becomes:

$$\Delta P = 1.71 \times 10^{-[illegible]} \times V^2 \times N.$$

Example - For the example above, the pressure drop is calculated to be:

$$\Delta P = 1.71 \times 10^{-[illegible]} \times 5^2 \times 16 = 0.68 \text{ inches } H_2O.$$

Nomenclature

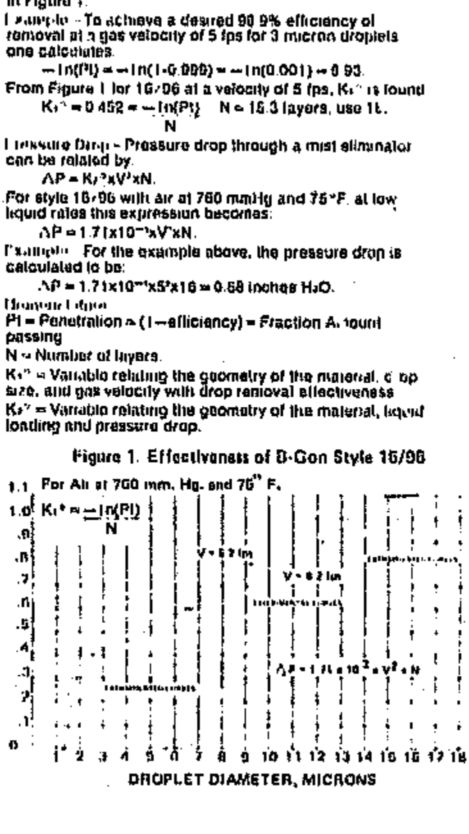
Pt = Penetration = (1 − efficiency) = Fraction Aerosol passing

N = Number of layers.

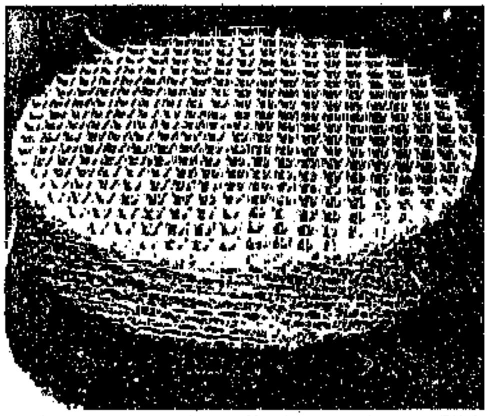
K_f = Variable relating the geometry of the material, drop size, and gas velocity with drop removal effectiveness

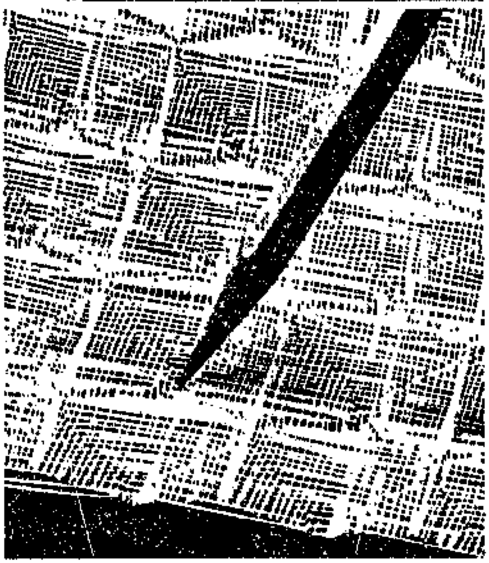
K_f' = Variable relating the geometry of the material, liquid loading and pressure drop.

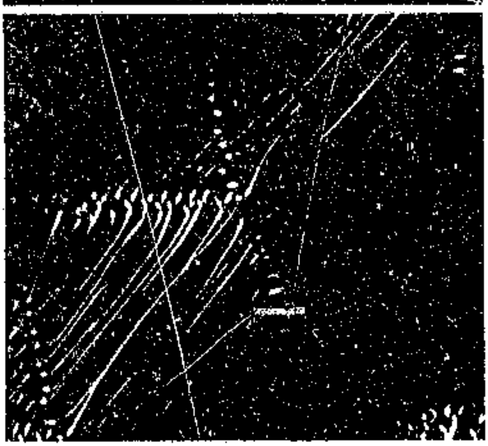
Figure 1. Effectiveness of B-Gon Style 16/96



Kon-Tane Tower Packing







Kon-Tane is an interlaced monofilament material for tower packing use. The material is designed to provide excellent breakup of the liquid phase, creating maximum surface area for mass transfer with the vapor phase. Its properties produce low pressure drop, prevent liquid holdup on and within the packing, and prevent excessive energy usage.

Its ladder-like arrangement of filaments or cylinders forms V-type double systems which intersect each other at right angles. A drop falling from one of the cylinders almost immediately hits the next, making new liquid surface available for mass transfer.

The range of filament diameters from which Kon-Tane can be manufactured permits use of larger diameter cylinders. These cylinders offer relatively less resistance to vapor flow due to lower surface area. It also permits variation in the void fraction of the material to suit process requirements.

While having approximately the same dry pressure drop ratings as 1½" raschig rings, Kon-Tane Style 37/94 does not flood at liquid feed rates in excess of 8600 $lbs/hr/ft^2$. Due to its inherent rigidity and strength, Kon-Tane can be installed in layered pads many feet thick using relatively simple supports. The material is flexible enough for the layers to be inserted through a manhole. Because of the uniform cross section of the material edge to edge, channeling at the wall of the vessel and throughout the material is minimized.

Kon-Tane tower packing is available in layered pads up to 6 inches in depth and 6 feet in diameter, and sheets up to 6 feet by 20 feet. Larger sizes can be manufactured in multiple-piece pads. Filament diameters are available from 16 mils to 62 mils. Kon-Tane tower packing is available in a variety of styles (see back page) manufactured from Kynar (Kynar is the trademark for Pennwalt Corporation's polyvinylidene fluoride resin), and polypropylene. Kynar will handle virtually any corrosive application up to 230°F. For higher temperature applications, other materials are available on special order.

Kon-Tane tower packing is available in layers up to 6 inches in depth and 6 feet in diameter.

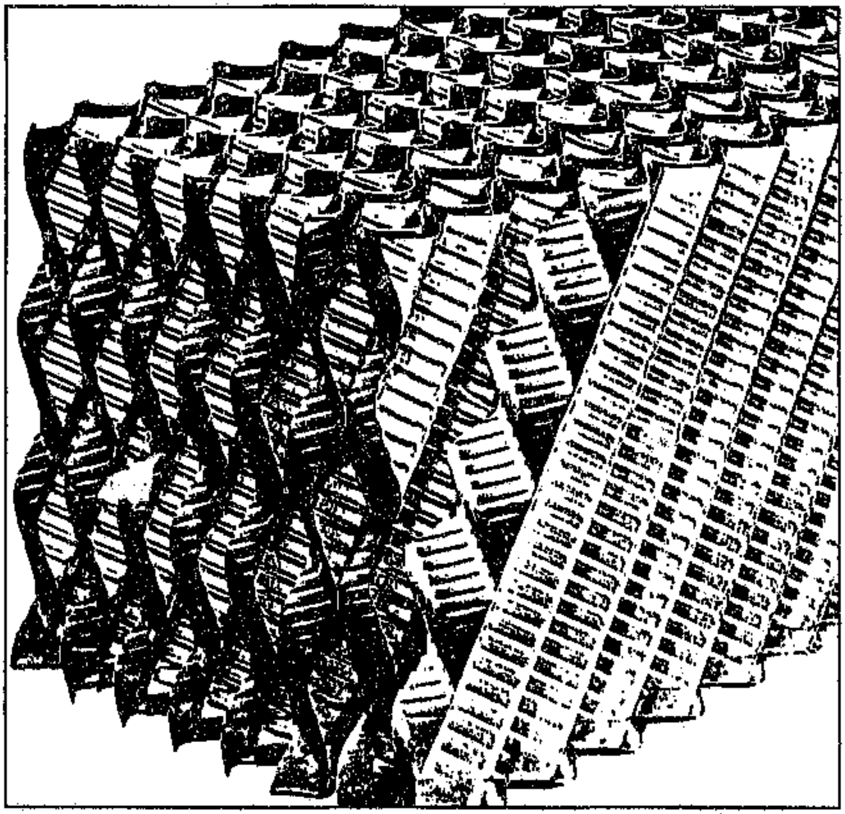
Ladder-like arrangement of filaments forms V-type double systems which intersect each other at right angles.

B-Gon and Kon-Tane utilize interlaced monofilaments with essentially all filaments oriented perpendicular to the gas flow.

APPENDIX G Specification of packing or fill used in test tower

The packing medium consisted of corrugated sheets joined together in a fluted configuration. The packing used was the 12 mm and 19 mm flute size fill supplied by Munters Euroform; specifications are given below:

Kühleinbau
Cooling Tower Fill C10
Kyltornsfyllning

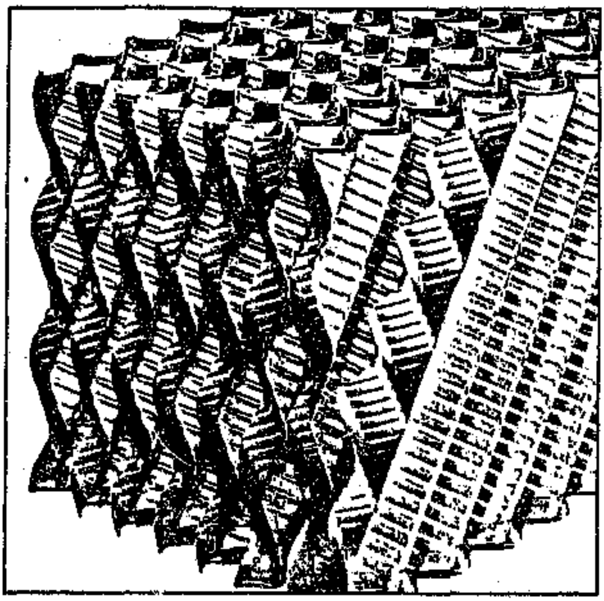


Drainagesystem.
Drainage system
Dränagesystem

D-5100 Aachen
P. O. Box 1089
Phone 0241/48411
Telex 832473

Typ Type Typ	C 10.12	C 10.15	C 10.19	C 10.27
Flute size Flute size Vellhöjd	12 mm	15 mm	19 mm	27 mm
Austauschfläche Surface of exchange Kontaktyta	243 m^2/m^3	187 m^2/m^3	148 m^2/m^3	112 m^2/m^3
Min. Regendichte Min. water load Vattenbelastning	8 m^3/m^2 h	8 m^3/m^2 h	5 m^3/m^2 h	3 m^3/m^2 h
Werkstoffe Materials Material	PVC	PVC	PVC	PVC
Materialstärke Material size Materialtjocklek	0,20 mm	0,20 mm	0,25 mm	0,40 mm
Gewicht Weight Vikt	35 kp/m^3	29 kp/m^3	27 kp/m^3	28 kp/m^3
Drainagesystem Drainage system Dränagesystem	HVT/AT	AT	AT	–
Standardabmessungen Standard dimensions Standarddimensioner	1200 x 300 x 300 mm			

C 10



CONSTRUCTION OF FILL:

CORRUGATED SHEETS ARE PILED UP AND JOINED TOGETHER WITH AN ADHESIVE OF SAME QUALITY AS FOIL MATERIAL. ALTERNATING POSITION OF SINGLE SHEETS GIVES HIGH STRENGTH.

ADDITIONAL REINFORCEMENT AND PROTECTION AGAINST DAMAGE OF SHEET EDGES BY CAPSIZING THE SHEET ENDS.

THERMAL QUALITIES:

HIGH EXCHANGE RATE AT COMPARABLY LOW PRESSURE DROP. THE MATERIAL STRUCTURE EFFECTS A SUFFICIENT TURBULENCE OF GASEOUS AND FLUID PHASES.

FLUTE SIZE OF SEVERAL DIMENSIONS FOR VARIOUS THERMAL SPECIFICATIONS. DRAINAGE SYSTEMS FOR HIGH WATER LOADS WHICH STOP THE PRESSURE DROP.

MATERIALS:

RIGID PVC (FLAME RESISTANT)
ASBESTOS (FIRE PROOFED)

APPLICATION:

CROSS OR COUNTER FLOW

APPENDIX H Expected uncertainty in the measurement of the energy balance

The uncertainty in each of the primary measurements have been estimated in the main text. This appendix shows, for a limited number of examples, how these uncertainties are propagated in the determination of the overall heat balance.

		Uncertainty in measurement 95% confidence limits	EXAMPLE 1A			EXAMPLE 1B			EXAMPLE 2A			EXAMPLE 2B			EXAMPLE 3A			EXAMPLE 3B		
			Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of uncertainties to cause most detrimental heat in-balance
Air flow rate	kg/s	2%	1,81	2,00	1,78	1,98	2,00	1,94	4,81	2,00	4,71	5,25	2,00	5,14	6,36	2,00	6,23	6,94	2,00	6,80
Inlet wet-bulb temp.	°C	0,1 °C	29,00	0,78	28,90	11,00	0,21	11,10	29,00	0,89	28,90	11,00	0,30	11,10	29,00	1,42	28,90	11,00	0,53	11,10
Inlet dry-bulb temp.	°C	0,1 °C	34,00	0,03	33,90	18,00	0,03	18,10	34,00	0,03	33,90	18,00	0,03	18,10	34,00	0,03	33,90	18,00	0,03	18,10
Outlet wet-bulb temp.	°C	0,1 °C	11,30	0,38	11,40	37,00	0,63	36,90	14,50	0,49	14,60	32,00	0,71	31,90	21,00	1,01	21,10	25,00	0,94	24,90
Outlet dry-bulb temp.	°C	0,1 °C	11,80	0,00	11,90	37,00	0,00	36,90	15,00	0,00	15,10	32,00	0,00	31,90	21,50	0,00	21,60	25,00	0,00	24,90
Water flow rate	kg/s	2%	12,00	2,00	12,24	12,00	2,00	12,24	6,00	2,00	6,12	6,00	2,00	6,12	3,00	2,00	3,06	3,00	2,00	3,06
Inlet water temp.	°C	0,1 °C	10,00	3,78	9,95	41,00	1,92	41,05	10,00	0,84	9,95	41,00	0,57	41,05	10,00	0,50	9,95	41,00	0,34	41,05
Outlet water temp.	°C	0,1 °C	12,56	3,72	12,66	36,10	1,96	36,03	21,66	0,84	21,76	22,30	0,51	22 20	29,13	0,52	29,23	12,96	0,33	12,86
Heat balance ratio		–	1,00	–	0,90	1,00	–	0,93	1,00	–	0,94	1,00	–	0,94	1,00	–	0,93	1,00	–	0,94
Uncertainty in heat balance $(e^2 + e^2 ...)^{1/2}$		–		6,07			4,00			3,23			3,02			3,40			3,06	

Table H.1 Expected uncertainty in the measurement of the energy balance

Continued/...

		Uncertainty in measurement 95% confidence limits	EXAMPLE 4A			EXAMPLE 4B			EXAMPLE 5A			EXAMPLE 5B			EXAMPLE 6A			EXAMPLE 6B		
			Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance	Balanced Data	Uncertainty in heat balance due to uncertainty in measurement %	Combination of un-certainties to cause most detrimental heat in-balance
Air flow rate	kg/s	2%	1,82	2,00	1,78	1,98	2,00	1,94	4,80	2,00	4,70	5,24	2,00	5,13	6,34	2,00	6,22	6,92	2,00	6,78
Inlet wet-bulb temp.	°C	0,1 °C	29,00	[illegible]	28,90	11,00	0,21	11,10	29,00	1,73	28,90	11,00	0,52	11,10	29,00	3,03	28,90	11,00	1,30	11,10
Inlet dry-bulb temp.	°C	0,1 °C	34,00	0,03	33,90	18,00	0,03	18,10	34,00	0,03	33,90	18,00	0,03	18,10	34,00	0,03	33,90	18,00	0,03	18,10
Outlet wet-bulb temp.	°C	0,1 °C	12,00	0,40	12,[illegible]0	37,00	0,63	36,90	22,50	1,31	22,60	25,00	0,91	24,90	25,50	2,60	[illegible]5,60	17,50	1,67	17,40
Outlet dry-bulb temp.	°C	0,1 °C	12,50	0,00	12,60	37,00	0,00	36,90	24,00	0,00	24,10	25,00	0,00	24,90	26,50	0,00	26,50	18,50	0,00	18,50
Water flow rate	kg/s	2%	12,00	2,00	12,24	12,00	2,00	12,24	6,00	2,00	6,12	6,00	2,00	6,12	3,00	2,00	3,06	3,00	2,00	3,06
Inlet water temp.	°C	0,1 °C	10,00	3,90	9,95	41,00	1,92	41,05	10,00	1,58	9,95	41,00	0,92	41,05	10,00	1,06	9,95	41,00	0,90	41,05
Outlet water temp.	°C	0,1 °C	12,49	3,83	12,59	36,08	1,96	35,98	16,18	1,58	16,28	30,70	0,92	30,60	19,32	1,08	19,42	30,38	0,89	30,28
Heat balance ratio		–	1,00	–	0,90	1,00	–	0,93	1,00	–	0,91	1,00	–	0,93	1,00	–	0,90	1,00	–	0,92
Uncertainty in heat balance $(e^2 + e^2 \ldots)^{\frac{1}{2}}$		–		6,22			4,00			4,21			3,29			5,12			3,75	

Table H.1 Expected uncertainty in the measurement of the energy balance

APPENDIX I Procedure for calculating heat balance and correcting data

As discussed in the main text the heat flow from either stream is simply calculated by the change in enthalpy.

The change in mass flow rate of the water due to condensation or evaporation is determined by a mass balance with the air stream, since the inlet and outlet moisture content of the air is known. The logic for correcting the errors in the data to create a heat balance is also presented in the main text. The following computer listing gives the exact procedure used to achieve this.

```
10    !                 PROCEDURE FOR CALCULATING HEAT BALANCE AND CORRECTING DATA
20    ! Only the relevant statements are shown
30    ! A(2) : Air pressure drop
40    ! A(3) : Water flow rate
50    ! A(4) : Air mass flow rate
60    ! A(5) : Air quantity
70    ! A(6) : Density of dry air
80    ! A(7) : Inlet water temperature
90    ! A(8) : Outlet water temperature
100   ! A(9) : Water temperature off packing
110   ! A(10): Inlet wet-bulb temperature
120   ! A(11): Inlet dry-bulb temperature
130   ! A(12): Outlet wet-bulb temperature
140   ! A(13): Outlet dry-bulb temperatore
150   ! A(14): Air duty
160   ! A(15): Water duty
170   ! A(16): Ratio of air duty / water duty
180   P2=83.5       !  Barometric pressure
190   ! CALCULATE NEW DUTY
200   G=0
210   P1=A(2)*.0005+P2
220   Fraction=.005
230   IF ABS(ABS(A1(14))-ABS(A1(15)))<1 THEN Fraction=.0005
240   G=G+Fraction   !Fraction of maximum error
250   ! Calculate new temperature and flow
260   Gap1=A(11)-A(10)
270   Gap2=A(13)-A(12)
280   IF ABS(A(14))>ABS(A(15)) THEN A1(5)=A(5)*(1-.02*G)
290   IF ABS(A(14))>ABS(A(15)) THEN A1(3)=A(3)*(1+.02*G)
300   IF ABS(A(14))<ABS(A(15)) THEN A1(5)=A(5)*(1+.02*G)
310   IF ABS(A(14))<ABS(A(15)) THEN A1(3)=A(3)*(1-.02*G)
320   IF A(7)>A(10) THEN GOTO 420
330   IF ABS(A1(14))>ABS(A1(15)) THEN A1(10)=A(10)-.1*G
340   IF ABS(A1(14))>ABS(A1(15)) THEN A1(12)=A(12)+.1*G
350   IF ABS(A1(14))>ABS(A1(15)) THEN A1(7)=A(7)-.1*G
360   IF ABS(A1(14))>ABS(A1(15)) THEN A1(8)=A(8)+.1*G
370   IF ABS(A1(14))<ABS(A1(15)) THEN A1(10)=A(10)+.1*G
380   IF ABS(A1(14))<ABS(A1(15)) THEN A1(12)=A(12)-.1*G
390   IF ABS(A1(14))<ABS(A1(15)) THEN A1(7)=A(7)+.1*G
400   IF ABS(A1(14))<ABS(A1(15)) THEN A1(8)=A(8)-.1*G
410   GOTO 500
420   IF ABS(A1(14))>ABS(A1(15)) THEN A1(10)=A(10)+.1*G
430   IF ABS(A1(14))>ABS(A1(15)) THEN A1(12)=A(12)-.1*G
440   IF ABS(A1(14))>ABS(A1(15)) THEN A1(7)=A(7)+.1*G
450   IF ABS(A1(14))>ABS(A1(15)) THEN A1(8)=A(8)-.1*G
460   IF ABS(A1(14))<ABS(A1(15)) THEN A1(10)=A(10)-.1*G
470   IF ABS(A1(14))<ABS(A1(15)) THEN A1(12)=A(12)+.1*G
480   IF ABS(A1(14))<ABS(A1(15)) THEN A1(7)=A(7)-.1*G
490   IF ABS(A1(14))<ABS(A1(15)) THEN A1(8)=A(8)+.1*G
500   A1(11)=A1(10)+Gap1
510   A1(13)=A1(12)+Gap2
520   P9=P1+.02*A(5)^2    !Pressure at flow measuring point
530   Esat1=.6105*EXP(17.27*A(10)/(237.3+A1(10)))
540   E1=(Esat1*((555.6-2.465*A1(10)+1.005*A1(11))-P1*1.005*(A1(11)-A1(10)))/(15
55.6+.139*A1(11)-1.599*A1(10)-Esat1*.14*(A1(11)-A1(10)))/P1)
550   A1(6)=(P1-E1)/(.287*(273.15+A1(11)))      !Density
560   A1(4)=A1(5)*A1(6)
570   Esat2=.6105*EXP(17.27*A1(12)/(237.3+A1(12)))
580   E2=(Esat2*(1555.6-2.465*A1(12)+1.005*A1(13))-P2*1.005*(A1(13)-A1(12))/(15
55.6+.139*A1(13)-1.599*A1(12)-Esat2*.14*(A1(13)-A1(12)))/P2)
590   A1=.622*E1/(P1-E1)    ! apparent specific humidity, W, of air in
600   A2=.622*E2/(P2-E2)    ! apparent specific humidity, W, of air out
610   MB=A1(5)*R*(A2-A1)    !Mass transfer
620   A1(15)=4.187*(A1(3)*A1(7)-(A1(3)-MB)*A1(8))    !Water duty
630   H1=1.005*A1(11)+A1*(2501+1.84*A1(11))    ! Enthalpy air in
640   H2=1.005*A1(13)+A2*(2501+1.84*A1(13))    ! Enthalpy air out
650   A1(14)=A1(5)*R*(H1-H2)       !  Air duty
660   A1(16)=-(A1(14)/A1(15))    !Ratio air duty/water duty
670   IF ABS(-(A1(14)/A1(15))-1)<.0001 THEN Dump_to_disk
680   GOTO 220
690   NEXT I
700   STOP
710   END
```

APPENDIX J Direct comparison between the overall transfer co·:fficient for evaporation tests and that for condensation tests

It is possible to predict the effects on the transfer coefficients of changes in temperature through an examination of the well established correlation for heat transfer data (eg, Equation J.1). Lefevre[102] has shown that the expectation is that the transfer coefficient will decrease with an increase in air and water temperature for the same water loading and air velocity. The indications are that this reduction might be of the order of 10 per cent for the full range of conditions considered here. However this sort of analysis has to inevitably be based on broad theoretical assumptions which have inherent limitations. Furthermore it is not clear how Lefevre took account of moisture content and its affect on the transport properties at the film condition. However, what could be significant is Lefevre's i ·..:ation that the water phase thermal resistance appe·r· to be highly affected by temperature conditions.

On the basis of the present set of data the opportunity existed to examine the effects on Nusselt number of variations in temperat.. e on an experimental basis. As described in the main text, values of the overall heat transfer coefficient were determined for each of the 160 tests and listed in Table 5.2. The experimental programme was structured so that, for the same flow and geometry conditions, equivalent tests were done for cold water/hot air and hot water/cold air conditions. This allows the effects of these changes in temperature conditions and direction of mass transfer to be examined directly and in isolation to the flow and geometry variables.

Heat transfer and mass transfer data are usually correlated in similar relationships as given by Equations 5.1 and 5.2. Through this similarity the mass transfer coefficient is related to the heat transfer coefficient. Recall that this approach is embodied in the computer simulator and thus an investigation of the overall energy transfer can focus attention on the heat transfer coefficient alone. Data on heat transfer coefficients are normally correlated through Equation 5.1, another common form of which is[96]:

$$Nu = a\,Re^{b}\,Pr^{z} \qquad (J.1)$$

(This is simply another form of Equation 5.1 following minor algebraic manipulation. Although the same nomenclature is used, the exponent terms will have different values.)

Equation J.1 often takes the form where an additive term is included on the right-hand side[49]. Bearing in mind that the analysis is comparative and that, as will be seen, Equation J.1 is used simply as a tool for differential adjustments of the Nusselt terms, the relative merits of the various correlations will not be debated here.

As will be seen later (Table J.1) the value of the Prandtl number, Pr, does not vary significantly in the present set of tests. Furthermore, the value of the exponent, c, is usually small ($c = 1 - z = 0{,}33$). Thus, variations in Pr do not play a significant part in the present comparative analysis and have been neglected.

The analysis now concentrates on the relationship:

$$Nu \propto Re^b \qquad (J.2)$$

which may be expanded to give :

$$\frac{h_c d}{k_{avf}} = a_1 \left[\frac{\rho_{av\infty} V\ d}{\mu_{avf}} \right]^b \qquad (J.3)$$

The velocity term referred to above is that of the free air stream. Ideally this term should be the relative velocity of the air in relation to the water surface. Again, considering the comparative nature of the analyses and that Equation J.3 is simply used as a tool for differential adjustment, the effect of the water velocity has been ignored.

Recall that all the transport properties are evaluated at the film condition. However, note that the reference mass velocity of the bulk air stream is applicable to the calculation of the Reynolds number. (This becomes obvious from the model of Reynolds flux discussed in Chapter 2). Of further interest at this stage is that the Stanton number, based on mass trnsfer data, simply represents the ratio of the Reynolds flux to the reference mass velocity of the bulk air stream.

$$St_m = m_{rf} / \rho_{av\infty} V \qquad (J.4)$$

An evaluation of Equation J.3 requires a knowledge of the values of the various transport properties. The representative values of these terms for each test have been determined by examining the experimental data in conjunction with the simulator. The computer simulator was used to determine the variation of the transport properties within the heat exchanger for each test and not only at the end states. This information was then used to determine, for each of the 160 tests, representative values of each of the transport properties within the heat exchanger. This has been done on a weighted mean basis with regard to the total heat transfer at each simulated section within the heat exchanger. These values are presented in Table J.1.

As mentioned earlier, note should be taken of the small variation in the value of Pr.

It will have been noted at this stage that the film coefficient and the surface area have been combined in a single overall term given as h_cA . It is impossible to determine independently the value of the surface area of contact available for heat and mass transfer. Apart from the difficulty in determining the surface area of the water drops in the spray above and below the packing, it is also apparent that the wetted area of the packing will depend on water flowrates.

The surface area is primarily a function of the packing geometry and the water flowrate; by matching these parameters it is possible to create an identical set of circumstances for cold water tests and for hot water tests in which the surface areas of contact are identical. Subsequent analysis can then be done on a comparative basis where ratios are taken and the surface area terms cancelled.

For each series of tests (both cold water/hot air and cold air/hot water tests for each packing configuration) the water flowrate was varied from 3 to 12 l/s in four steps having nominal values of 3; 6; 9; and 12 l/s. For each of these water flowrates the flowrate of the air was varied from 2 to 7 kg/s, again in four steps with nominal values of 2; 3,7; 5,3; and 7 kg/s. Thus, each series of tests consisted of 16 sets of measurements at the nominal, standard flow settings. Practically, it was extremely difficult to control the flows to the exact nominal values and the actual values varied slightly. For a direct comparison of corresponding cold water and hot water tests, it was necessary to marginally adjust each of the measured values to the exact nominal conditions.

Including a surface area term in Equation J.3, gives:

$$Nu.A = \frac{h_c A\ d}{k_{avf}} = a_1 \left[\frac{\rho_{av\infty}\ V\ d}{\mu_{avf}} \right]^b A \qquad (J.5)$$

For a single packing geometry, the surface area will be related to water flowrate, hence:

$$Nu.A = \frac{h_c A\ d}{k_{avf}} = a_1 \left[\frac{\rho_{av\infty}\ V\ d}{\mu_{avf}} \right]^b f_1(\dot{m}_w) \qquad (J.6)$$

For a meaningful comparison to be drawn between Nu_{cold} and Nu_{hot}, the terms on the right-hand side of Equation J.5 must be identical. (The subscripts cold and hot refer to the cold water/hot air and hot water/cold air tests respectively.) Marginal adjustments for the slight variations from the nominal values of each test were done on a differential basis using equations which had been fitted to each of the 10 sets of test data. The fitting of these equations involved a correlation

$$Nu.A = K_6\dot{m}_w + K_7Re + K_8\dot{m}_wRe + K_9\dot{m}_w^2 + K_{10}Re^2 + K_{11}\dot{m}_w^2Re + K_{12}\dot{m}_wRe^2 + K_{13}\dot{m}_w^2Re^2 \qquad (J.7)$$

Results of the curve fitting exercise and values of the coefficients are shown in Table J.2. In each case the correlation was excellent.

Marginal adjustments to the actual values of Nu.A were then done through:

$$\Delta\, Nu.A = \frac{\partial(Nu.A)\ \Delta Re}{\partial\ Re} + \frac{\partial(Nu.A)\ \Delta\dot{m}_w}{\partial\ \dot{m}_w} \qquad (J.8)$$

where ΔRe and Δm_w are the marginal differences between the measured and nominal values of Re and the water flowrate respectively. Δ Nu.A is the marginal difference between that calculated from the measurements and the expected value at the nominal flow settings.

The adjusted nominal values have been compared by examining the ratio of the cold water/hot air values to the hot water/cold air values and the results given as the ratio of the Nusselt numbers in Table J.3.

Based on the well accepted historic use of the relationship $Nu = a\ Re^b$, the high quality of the data and the care taken to match equivalent cold and hot operating conditions, it should be expected that the ratio $Nu_{cold/hot}$ would have values of close to unity.

From an examination of Table J.3 it can be seen that over the full range of tests, the value of the ratio $Nu_{cold/hot}$ varied from 0,88 to 1,49. The value was generally greater than unity and on an average basis the value of Nu_{cold} was 7 per cent greater than the value of Nu_{hot}. However, the wide variation in these values is worth closer examination.

A careful consideration of the value of the Nu cold/hot ratio has not identified any systematic and consistent relationship between its value and the main parameters such as the water flow, air flow, temperature conditions and any combination of these terms. For example, it was felt that there would be merit in examining the relationship between $Nu_{cold/hot}$ and the ratio of the density of the film and free stream condition for the cold and hot conditions. This data is plotted in Figure J.1, and there is clearly no trend evident.

This observation and the wide variation in values of the $Nu_{cold/hot}$ ratio identifies two main questions. First, is the value of h_cA calculated in the correct manner? Second, is the surface area term indeed identical for equivalent cold water and hot water tests? Each of these questions is discussed in turn below.

The basic equation for the total heat transfer from a wet surface is given as:

$$q_t = h_c A \; (t_w - t_{db} + \lambda B') \qquad (J.9)$$

The definition of the transfer coefficient is intimately linked to the definition of the overall driving force term. However, once defined and measured, the values of the transfer coefficient are correlated, for future use, in a manner that is essentially independent of the driving force conditions under which it was measured. Thus, the basic method of analysis uses two distinct terms and the underlying premise is that, in the true physical sense, the two parameters should be independent of each other.

[Note that, notwithstanding the above, the transfer coefficient does not really describe the physical mechanisms but rather the overall effects thereof.]

However, as discussed earlier, it can be expected that in the presence of mass transfer, the value of the mass transfer coefficient would be affected by the migration of vapour, and would depend on the extent of the mass transfer itself. This led to the introduction of the logarithmic correction term given below and shown graphically in Figure J.2.

$$\dot{m}''_{tf} \quad \alpha \quad \frac{\ln (1 + B)}{B} \qquad (J.10)$$

Accepting the validity of this correction term and noting that it is included in the bracketed driving force term of Equation J.9, it seems acceptable to anticipate that the transfer coefficient and the overall driving force term would be independent. (Note that the value of the transfer coefficient is related to pure heat transfer data only.)

Thus, the value of Nu should be essentially independent of whether hot water or cold water is used. However, the large variation in the values in Table J.3 does not support this observation and generally Nu_{cold} is greater than Nu_{hot}.

The simplicity of the basic analogy and the basic logarithmic correction term must be questioned. Recall Goff's[41] comment quoted earlier with regard to 'inaccurate conjecture based upon an unwarranted faith in the ultimate simplicity of nature'; this may well be applicable here. Certainly Spalding emphasizes that the simple procedure must be abandoned for all except the roughest calculations. The present set of data appear to highlight these limitations.

One possible conclusion is that the logarithmic correction term does not comply with reality. Examining this issue more deeply indeed reveals some evidence of its inaccuracy. Spalding[67] discusses experimental data[80,81] which indicate that the driving force might have a more dominant effect on the value of the transfer coefficient than would be indicated through Equation J.10. Even more evidence of this strong dependency comes from theoretical laminar boundary layer studies. Evans[56] presents information for flow over a flat plate for various Prandtl and Schmidt numbers. Evans' findings are repeated in Figure J.2, for the appropriate Prandtl and Schmidt numbers. For the range of conditions being considered, the value of the driving force, B, varies between -0,1 and +0,1. Figure J.2 indicates that for condensation situations (cold water), the value of the actual mass transfer coefficient might be as much as 3 per cent higher than determined by the basic logarithmic correction factor. The opposite effect occurs for the hot water situation. For extreme cases, the comparative differences could be as much as 6 per cent. (Note that the nature of the dependency is such that the transfer coefficient decreases as the conditions become more evaporative.)

If the multiplying factor resulting from the boundary layer studies had been used in place of the normal logarithmic factor within the computer program for calculating the values of $h_c A$, then the resulting ratio of $Nu_{cold/hot}$ would be somewhat decreased. Thus, here is some further evidence that the mass transfer affects the value of the transfer coefficient to a greater extent than the widely used logarithmic factor would predict.

These present arguments cannot be regarded as any proof of this fact, but it is an issue worth pursuing further. One possible solution might be the use of separate transfer coefficients for heat and mass transfer. This is an approach that a number of other researchers(87,88) have used. From practical point of view, the adoption of this approach would be unfortunate since the simplicity and user-friendliness of all the methods of analysis rely heavily on the use of a single combined transfer coefficient. Another course of action to follow would be the development of a heat and mass transfer analogy and a correction factor (for the mass transfer effect on the transfer coefficient) that would decribe both this present set and other data. In such a development the basic premise must be that the transfer coefficient would be a reference value (applicable under circumstances of no mass transfer) which would be independent of the so-called corrected driving force. (The driving force term would include the analogy relationship and the effect of mass transfer correction factor.)

In essence, this proposal would be aimed at forcing $Nu_{cold/hot}$ to take on a value of unity, which is to be expected from using the 'film' coefficient concept in the first place. Whatever course of action is taken, this present work has highlighted a number of limitations and has again indicated the need for an independent, specific treatment f.r water-air systems (see Chapter 1).

The second question raised earlier was with regard to the surface areas being identical for the cold water and the hot water tests. Recall the assumption that the extent of the surface area would depend primarily on water flow, and that for the same water flow, the same wetted surface area would be created (for the same geometry), whether the water was hot or cold. Considering this in further detail, the interaction between air flow and water flow could be expected to affect the surface area to some extent. This interaction would be driven by phenomena related to Reynold's number. The prevailing logic has been that this effect was also accounted for by making the comparison of Nu_{cold} to Nu_{hot} at the same Reynold's air flow numbers. It should also be noted that the physical properties of water that would affect the formation of the water surfaces, namely density, viscosity and surface tension, do indeed vary over the range of conditions being considered. These properties are given in Table J.4. It can be seen that the viscosity varies by up to 300 per cent and the surface tension by 10 per cent over the full range of conditions. The mechanisms involved in the formation of all the water surfaces are extremely complex, but probably deserve some further research. Lefevre[102] indicates that the water phase thermal resistance could be significantly affected by changes in water temperature and, in examining the formation of the water surfaces, this aspect should also be investigated.

Conclusions

- Values of the ratio $Nu_{cold/hot}$ are expected to have a value of close to unity. For the 90 sets of data the mean was 1,07 with a range from 0,88 to 1,49.

- The wide range of values of $Nu_{cold/hot}$ encountered is probably an indication of the limitations of the simple heat and mass transfer analogy employed and of the basic logarithmic correction term used to account for the effect of mass transfer on the transfer coefficient.

- Two further areas of research outside the scope of the present study are suggested. The first is an examination of the heat and mass transfer analogy and the correction factor on the basic premise that $Nu_{cold/hot}$ should equal unity. The second is a study of the effect of water viscosity and surface tension on the formation of wet surface areas in packed towers.

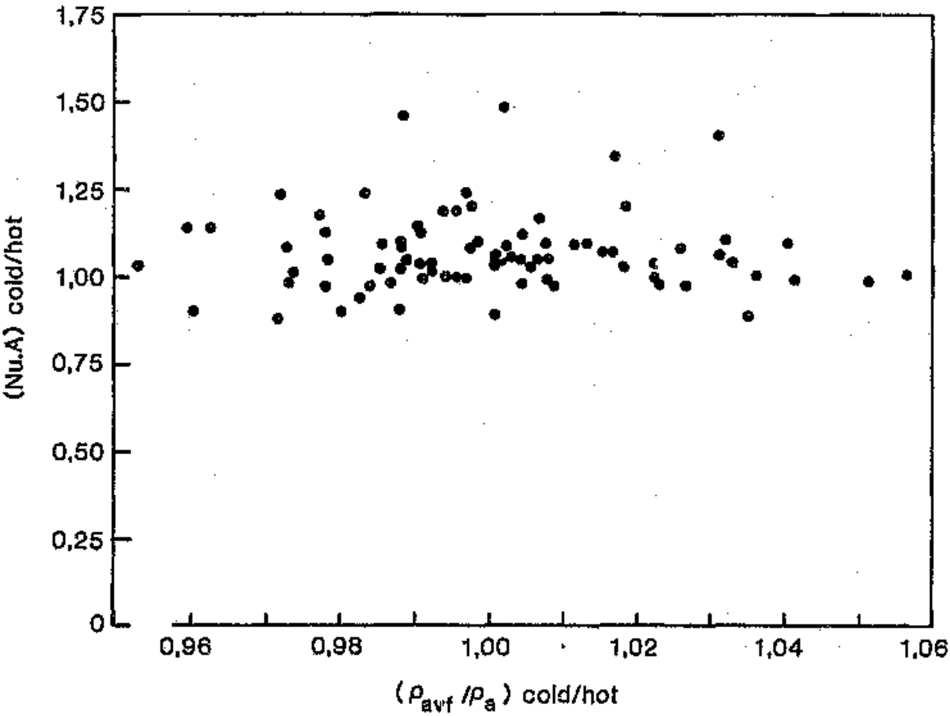


Figure J.1 Relationship between Nu.A and the ratio of the film to bulk stream air density

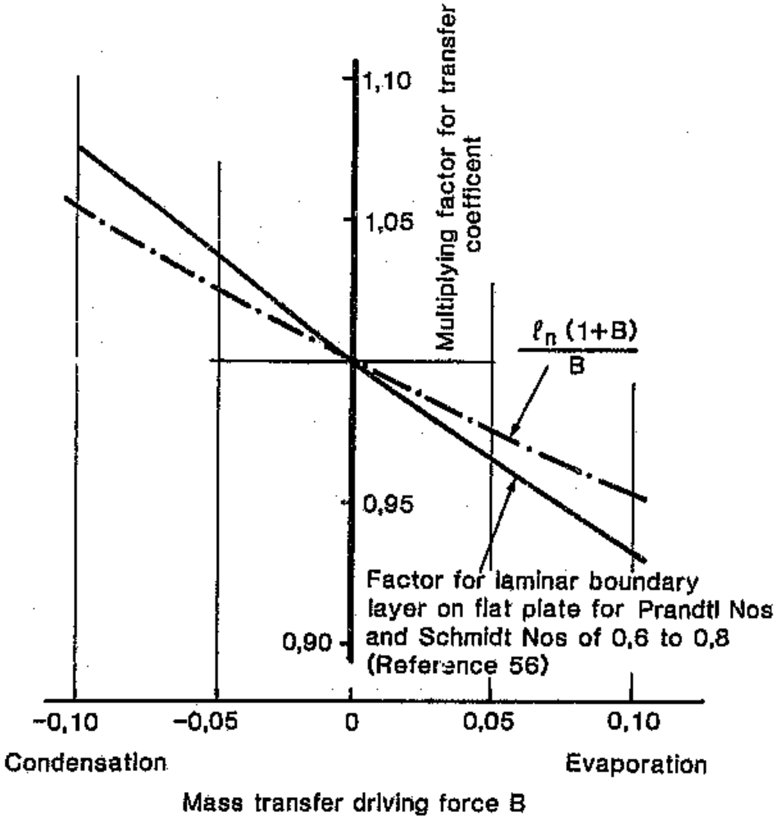


Figure J.2 Effect of the mass transfer driving force, B, on the mass transfer coefficient (multiplying factor)

TEST No.	FILM COND. Kavf *10-2 (W/mK)	FILM VISC. μ_{avf} *10-5 (Ns/m^2)	FILM DENS. ρ_{avf} kg/m^3	BULK DENS. ρ_a kg/m^3	FILM SP. HEAT Cavf J/kgK	FILM DIFF. Davf *10-5 (m^2/s)	Pr	Sc
1	2.591	1.829	0.964	0.945	[illegible]	3.109	0.722	0.611
2	2.573	1.818	0.966	0.941	1021	3.087	0.722	0.609
3	2.559	1.810	0.960	0.937	1020	3.100	0.721	0.608
4	2.553	1.806	0.937	0.916	1019	3.173	0.721	0.608
5	2.581	1.823	0.967	0.951	1022	3.091	0.722	0.610
6	2.563	1.812	0.970	0.946	1020	3.072	0.721	0.609
7	2.353	1.806	0.962	0.943	1019	3.088	0.721	0.608
8	2.548	1.803	0.945	0.927	1019	3.142	0.721	0.608
9	2.587	1.827	0.962	0.936	1022	3.113	0.722	0.610
10	2.552	1.805	0.974	0.954	1018	3.052	0.720	0.608
11	2.541	1.799	0.966	0.951	1018	3.066	0.720	0.607
12	2.570	1.816	0.928	0.917	1021	3.214	0.722	0.609
13	2.567	1.815	0.966	0.945	1020	3.086	0.721	0.609
14	2.557	1.808	0.967	0.950	1019	3.075	0.721	0.608
15	2.551	1.805	0.962	0.946	1019	3.087	0.721	0.608
16	2.543	1.800	0.952	0.939	1018	3.114	0.720	0.607
17	2.617	1.845	0.950	0.995	1027	3.168	0.724	0.613
18	2.653	1.867	0.923	0.967	1035	3.278	0.728	0.617
19	2.659	1.871	0.902	0.944	1037	3.359	0.729	0.618
20	2.666	1.875	0.865	0.907	1040	3.515	0.732	0.620
21	2.611	1.841	0.951	0.997	1026	3.161	0.724	0.612
22	2.641	1.859	0.920	0.973	1032	3.255	0.727	0.616
23	2.650	1.865	0.908	0.948	1035	3.333	0.728	0.617
24	2.656	1.869	0.876	0.916	1038	3.463	0.730	0.619
25	2.628	1.852	0.939	0.989	1029	3.214	0.725	0.614
26	2.627	1.851	0.933	0.975	1029	3.231	0.725	0.614
27	2.642	1.860	0.912	0.950	1033	3.314	0.727	0.616
28	2.646	1.863	0.888	0.925	1035	3.411	0.728	0.617
29	2.615	1.844	0.940	0.986	1027	3.201	0.724	0.613
30	2.622	1.848	0.931	0.973	1029	3.235	0.725	0.614
31	2.634	1.856	0.915	0.953	1031	3.301	0.726	0.615
32	2.637	1.857	0.896	0.933	1033	3.373	0.727	0.616

Table J.1 Representative values of the thermodynamic transport properties (mean values weighted by total heat transfer for each of 100 segments of heat exchanger)

Continued/...

TEST No.	FILM COND. Kavf *10-2 (W/mK)	FILM VISC. μavf *10-5 (Ns/m^2)	FILM DENS. ρavf kg/m^3	BULK DENS. ρa kg/m^3	FILM SP. HEAT Cavf J/kgK	FILM DIFF. Davf *10-5 (m^2/s)	Pr	Sc
33	2.584	1.825	0.965	0.954	1022	3.101	0.722	0.610
34	2.564	1.813	0.976	0.963	1020	3.052	0.721	0.609
35	2.557	1.809	0.979	0.965	1019	3.038	0.721	0.608
36	2.558	1.809	0.977	0.962	1019	3.045	0.721	0.608
37	2.587	1.827	0.951	0.943	1023	3.145	0.722	0.610
38	2.562	1.811	0.967	0.957	1020	3.079	0.721	0.609
39	2.545	1.801	0.976	0.963	1018	3.039	0.720	0.607
40	2.562	1.811	0.964	0.955	1020	3.086	0.721	0.608
41	2.592	1.823	0.934	0.928	1023	3.199	0.722	0.610
42	2.558	1.809	0.931	0.943	1020	3.128	0.721	0.608
43	2.544	1.801	0.960	0.949	1018	3.089	0.721	0.607
44	2.563	1.812	0.946	0.941	1020	3.148	0.721	0.609
45	2.575	1.819	0.903	0.899	1022	[illegible].304	0.722	0.610
46	2.554	1.807	0.922	0.917	1020	3.222	0.721	0.609
47	2.560	1.810	0.922	0.919	1020	3.231	0.721	0.609
48	2.559	1.810	0.921	0.917	1020	3.234	0.721	0.609
49	2.640	1.859	0.933	0.968	1032	3.238	0.727	0.616
50	2.640	1.859	0.934	0.967	1032	3.235	0.727	0.616
51	2.657	1.869	0.924	0.961	1036	3.274	0.729	0.618
52	2.665	1.874	0.918	0.959	1037	3.372	0.730	0.619
53	2.627	1.851	0.926	0.960	1030	3.256	0.726	0.615
54	2.628	1.852	0.928	0.959	1030	3.251	0.726	0.615
55	2.648	1.864	0.916	0.951	1034	3.304	0.728	0.617
56	2.656	1.869	0.969	0.948	1036	3.332	0.729	0.618
57	2.619	1.846	0.906	0.939	1030	3.326	0.726	0.614
58	2.615	1.844	0.912	0.941	1029	3.303	0.725	0.614
59	2.627	1.851	0.906	0.935	1031	3.331	0.726	0.615
60	2.648	1.864	0.890	0.925	1035	3.405	0.729	0.617
61	2.613	1.842	0.877	0.909	1030	3.438	0.726	0.614
62	2.607	1.839	0.881	0.909	1028	3.422	0.725	0.613
63	2.626	1.851	0.870	0.897	1032	3.480	0.727	0.615
64	2.643	1.861	0.858	0.890	1036	3.539	0.729	0.618

Table J.1 (Cont.)

Continued/...

TEST No.	FILM COND. Kavf *10-2 (W/mK)	FILM VISC. μavf *10-5 (Ns/m²)	FILM DENS. ρavf kg/m³	BULK DENS. ρa kg/m³	FILM SP. HEAT Cavf J/kgK	FILM DIFF. Davf *10-5 (m²/s)	Pr	Sc
65	2.587	1.826	0.960	0.959	1023	3.117	0.722	0.610
66	2.560	1.810	0.978	0.969	1019	3.044	0.721	0.608
67	2.571	1.817	0.973	0.961	1021	3.066	0.722	0.609
68	2.562	1.812	0.973	0.962	1020	3.054	0.721	0.609
69	2.583	1.824	0.942	0.943	1023	3.172	0.722	0.610
70	2.564	1.813	0.962	0.957	1020	3.095	0.721	0.609
71	2.563	1.812	0.964	0.956	1020	3.088	0.721	0.609
72	2.552	1.806	0.968	0.956	1019	3.069	0.721	0.608
73	2.577	1.828	0.907	0.908	1022	3.292	0.722	0.610
74	2.550	1.809	0.937	0.935	1020	3.174	0.721	0.608
75	2.549	1.803	0.949	0.944	1019	3.127	0.721	0.608
76	2.545	1.801	0.949	0.940	1018	3.127	0.721	0.608
77	2.554	1.907	0.858	0.858	1020	3.462	0.722	0.609
78	2.549	1.804	0.888	0.888	1019	3.347	0.721	0.608
79	2.550	1.804	0.899	0.896	1019	3.311	0.721	0.608
80	2.547	1.802	0.905	0.899	1019	3.290	0.721	0.608
81	2.630	1.853	0.935	0.964	1030	3.229	0.726	0.615
82	2.655	1.866	0.923	0.954	1036	3.281	0.729	0.618
83	2.654	1.868	0.925	0.959	1035	3.273	0.728	0.617
84	2.668	1.876	0.915	0.952	1039	3.315	0.730	0.619
85	2.618	1.846	0.918	0.946	1029	3.282	0.726	0.614
86	2.643	1.861	0.900	0.937	1034	3.330	0.728	0.617
87	2.646	1.863	0.910	0.939	1035	3.328	0.726	0.617
88	2.660	1.871	0.900	0.933	1038	3.372	0.730	0.619
89	2.611	1.841	0.883	0.911	1029	3.411	0.726	0.614
90	2.633	1.855	0.876	0.903	1034	3.457	0.728	0.616
91	2.640	1.859	0.874	0.902	1035	3.467	0.729	0.617
92	2.654	1.868	0.864	0.894	1038	3.521	0.731	0.619
93	2.606	1.838	0.830	0.858	1030	3.635	0.727	0.614
94	2.625	1.850	0.821	0.848	1035	3.699	0.729	0.617
95	2.633	1.855	0.817	0.845	1036	3.729	0.730	0.617
96	2.650	1.865	0.812	0.843	1040	3.763	0.732	0.620

Table J.1 (Cont.)

Continued/...

TEST No.	FILM COND. Kavf *10-2 (W/mK)	FILM VISC. μavf *10-5 (Ns/m²)	FILM DENS. ζavf kg/m³	BULK DENS. ζa kg/m³	FILM SP. HEAT Cavf J/kgK	FILM DIFF. Davf *10-5 (m²/s)	Pr	Sc
97	2.584	1.825	0.965	0.954	1022	3.097	0.722	0.610
98	2.561	1.811	0.970	0.965	1020	3.044	0.721	0.608
99	2.560	1.811	0.970	0.965	1020	3.043	0.721	0.608
100	2.566	1.814	0.973	0.959	1020	3.063	0.721	0.609
101	2.588	1.828	0.955	0.945	1023	3.133	0.722	0.611
102	2.589	1.827	0.957	0.951	1023	3.128	0.722	0.610
103	2.575	1.820	0.963	0.955	1021	3.099	0.722	0.609
104	2.568	1.815	0.964	0.952	1020	3.092	0.721	0.609
105	2.584	1.825	0.942	0.933	1023	3.175	0.722	0.610
106	2.566	1.814	0.953	0.944	1020	3.126	0.721	0.609
107	2.565	1.813	0.953	0.948	1020	3.125	0.721	0.609
108	2.561	1.811	0.952	0.945	1020	3.127	0.721	0.608
109	2.580	1.823	0.908	0.903	1023	3.289	0.723	0.610
110	2.574	1.819	0.922	0.918	1022	3.235	0.722	0.610
111	2.564	1.813	0.927	0.922	1021	3.213	0.722	0.609
112	2.558	1.809	0.925	0.918	1020	3.218	0.721	0.608
113	2.637	1.857	0.938	0.973	1031	3.220	0.726	0.615
114	2.651	1.866	0.938	0.966	1034	3.254	0.728	0.617
115	2.659	1.871	0.925	0.962	103[illegible]	3.274	0.729	0.618
116	2.665	1.874	0.920	0.959	1037	3.295	0.729	0.619
117	2.625	1.850	0.935	0.971	1029	3.225	0.725	0.614
118	2.638	1.858	0.928	0.962	1032	3.256	0.727	0.616
119	2.645	1.862	0.923	0.957	1033	3.276	0.727	0.616
120	2.655	1.868	0.915	0.953	1035	3.309	0.729	0.618
121	2.614	1.843	0.923	0.957	1028	3.262	0.725	0.613
122	2.629	1.852	0.916	0.948	1031	3.296	0.726	0.615
123	2.635	1.856	0.912	0.944	1032	3.312	0.727	0.615
124	2.648	1.864	0.901	0.936	1035	3.361	0.728	0.617
125	2.606	1.838	0.898	0.930	1028	3.350	0.725	0.613
126	2.621	1.847	0.891	0.922	1030	3.387	0.726	0.615
127	2.625	1.850	0.880	0.917	1031	3.400	0.726	0.615
128	2.642	1.860	0.873	0.906	1035	3.473	0.729	0.617

Table J.1 (Cont.)

Continued/...

TEST No.	FILM COND. Kavf *10-2 (W/mK)	FILM VISC. μavf *10-5 (Ns/m²)	FILM DENS. ρavf kg/m³	BULK DENS. ρa kg/m³	FILM SP. HEAT Cavf J/kgK	FILM DIFF. Davf *10-5 (m²/s)	Pr	Sc
129	2.573	1.818	0.976	0.965	1021	3.076	0.721	0.609
130	2.561	1.811	0.977	0.968	1020	3.047	0.721	0.608
131	2.551	1.805	0.982	0.970	1018	3.023	0.721	0.608
132	2.569	1.816	0.972	0.961	1021	3.068	0.721	0.609
133	2.584	1.825	0.949	0.947	1023	3.150	0.722	0.610
134	2.560	1.810	0.967	0.962	[illegible]	3.077	0.721	0.608
135	2.555	1.808	0.970	0.961	1019	3.063	0.721	0.608
136	2.558	1.809	0.966	0.959	1019	3.078	0.721	0.608
137	2.577	1.821	0.925	0.924	1022	3.226	0.722	0.610
138	2.556	1.808	0.948	0.946	1019	3.134	0.721	0.608
139	2.561	1.811	0.948	0.939	1020	3.140	0.721	0.609
140	2.556	1.808	0.948	0.942	1019	3.136	0.721	0.608
141	2.565	1.814	0.885	0.884	1021	3.366	0.722	0.609
142	2.553	1.806	0.915	0.915	1019	3.247	0.721	0.608
143	2.549	1.803	0.923	0.920	1019	3.219	0.721	0.608
144	2.553	1.806	0.916	0.912	1019	3.249	0.721	0.608
145	2.615	1.843	0.946	0.972	1027	3.181	0.724	0.613
146	2.637	1.853	0.939	0.968	1030	3.212	0.726	0.615
147	2.638	1.858	0.935	0.967	1032	3.232	0.727	0.615
148	2.626	1.851	0.940	0.971	1029	3.200	0.725	0.614
149	2.602	1.836	0.937	0.961	1026	3.206	0.724	0.612
[illegible]	[illegible]	1.849	[illegible]	0.955	1029	3.245	0.725	0.614
151	2.632	1.854	0.924	0.953	1031	3.269	0.726	0.615
152	2.622	1.848	0.929	0.956	1029	3.247	0.725	0.614
153	2.594	1.831	0.914	0.938	1025	3.286	0.724	0.612
154	2.614	1.843	0.907	0.931	1029	3.325	0.725	0.614
155	2.626	1.851	0.901	0.927	1031	3.354	0.726	0.615
156	2.614	1.843	0.907	0.932	1028	3.324	0.725	0.613
157	2.598	1.829	0.874	0.898	1026	3.437	0.724	0.612
158	2.600	1.839	0.868	0.892	1029	3.476	0.726	0.614
159	2.621	1.847	0.860	0.885	1031	3.522	0.727	0.615
160	2.608	1.839	0.866	0.889	1029	3.493	0.725	0.613

Table J.1 (Cont.)

Continued/...

TEST NUMBERS	FLUTE	DEPTH mm	HOT/COLD WATER	R	K6	K7 $\times 10^{-4}$	K8 $\times 10^{-4}$	K9 $\times 10^{-2}$	K10 $\times 10^{-7}$	K11 10^{-5}	K12 10^{-7}	K13 10^{-8}
1 - 16	SPRAY ONLY		COLD	0,989	0,027	-8,71	3,63	0,07	4,47	-1,79	-1,71	1,15
17 - 32	SPRAY ONLY		HOT	0,997	0,084	-8,20	1,99	-0,73	5,21	0,33	-1,22	0,17
33 - 48	12	600	COLD	0,977	0,411	1,19	0,63	-2,61	-0,40	-0,08	0,55	-0,14
49 - 64	12	600	HOT	0,999	0,296	-6,27	5,16	-1,78	1,91	-3,53	-0,67	0,63
65 - 80	12	1 200	COLD	1,000	0,209	-4,73	9,83	-2,15	2,10	-4,53	-1,62	0,81
81 - 96	12	1 200	HOT	1,000	0,332	-4,59	8,74	-3,52	3,57	-3,05	-1,76	0,59
97 - 112	19	600	COLD	1,000	0,432	-4,15	3,64	-2,64	1,32	-1,95	-0,37	0,23
113 - 128	19	600	HOT	1,000	0,419	-6,25	3,93	-2,51	1,61	-2,26	-0,39	0,27
129 - 144	19	1 200	COLD	1,000	0,462	-2,81	5,30	-2,41	1,25	-2,95	-0,33	0,24
145 - 160	19	1 200	HOT	1,000	0,473	3,37	3,87	-4,14	1,05	-0,96	-0,41	0,11

Table J.2 Coefficients of curve fitting for $Nu.A = f(Re, \dot{m}_w)$

	NOMINAL WATER FLOW (kg/s)	NOMINAL AIR FLOW (kg/s)	NOMINAL AIR VELOCITY (m/s)	NOMINAL REYNOLD NUMBER	Nu.A Cold/Hot
	3,0	2,0	1,5	390	1,022
	6,0	2,0	1,5	390	1,054
	9,0	2,0	1,5	390	1,070
	12,0	2,0	1,5	390	1,202
	3,0	3,7	2,5	680	1,089
	6,0	3,7	2,5	680	1,099
	9,0	3,7	2,5	680	1,091
	12,0	3,7	2,5	680	1,164
	3,0	5,3	4,0	950	1,048
	6,0	5,3	4,0	950	1,187
	9,0	5,3	4,0	950	1,120
	12,0	5,3	4,0	950	0,989
	3,0	7,0	5,0	1 310	1,126
	6,0	7,0	5,0	1 310	1,189
	9,0	7,0	5,0	1 310	1,239
	12,0	7,0	5,0	1 310	1,202
					1,118 mean

Note

The characteristic dimension was taken as the flute size of the packing, that is 12mm or 19mm. For the spray situation a characteristic dimension of 5mm (approximating drop diameter) was used. However, the exact choice of these values is not important since the analysis involves direct comparison for similar geometries.

Table J.3 Ratio of Nu.A cold/hot for corresponding flow situations

Continued/...

NOMINAL WATER FLOW (kg/s)	NOMINAL AIR FLOW (kg/s)	NOMINAL AIR VELOCITY (m/s)	NOMINAL REYNOLD NUMBER	Nu.A Cold/Hot
TESTS 33-64 (12mm flute 0,6m deep)				
3,0	2,0	1,5	900	0,995
6,0	2,0	1,5	900	0,984
9,0	2,0	1,5	900	1,002
12,0	2,0	1,5	900	1,405
3,0	3,7	2,5	1 603	0,979
6,0	3,7	2,5	1 630	0,980
9,0	3,7	2,5	1 630	1,069
12,0	3,7	2,5	1 630	1,343
3,0	5,3	4,0	2 470	0,973
6,0	5,3	4,0	2 470	0,997
9,0	5,3	4,0	2 470	1,086
12,0	5,3	4,0	2 470	1,485
3,0	7,0	5,0	3 520	1,011
6,0	7,0	5,0	3 520	1,127
9,0	7,0	5,0	3 520	1,239
12,0	7,0	5,0	3 520	1,464
				1,134 mean
TESTS 65-96 (12mm flute 1,2m deep)				
3,0	2,0	1,5	900	0,039
6,0	2,0	1,5	900	0,880
9,0	2,0	1,5	900	1,004
12,0	2,0	1,5	900	0,989
3,0	3,7	2,5	1 603	0,940
6,0	3,7	2,5	1 630	1,047
9,0	3,7	2,5	1 630	0,975
12,0	3,7	2,5	1 630	1.042
3,0	5,3	4,0	2 470	0,877
6,0	5,3	4,0	2 470	1,047
9,0	5,3	4,0	2 470	1,035
12,0	5,3	4,0	2 470	1,053
3,0	7,0	5,0	3 520	0,901
6,0	7,0	5,0	3 520	1,034
9,0	7,0	5,0	3 520	1,137
12,0	7,0	5,0	3 520	1,236
				1,015 mean

Table J.3 Ratio of Nu.A $_{cold/hot}$ for corresponding flow situations.

Continued/...

TESTS 97-128 (19mm flute 0,6m deep)	NOMINAL WATER FLOW (kg/s)	NOMINAL AIR FLOW (kg/s)	NOMINAL AIR VELOCITY (m/s)	NOMINAL REYNOLD NUMBER	Nu.A Cold/Hot
	3,0	2,0	1,5	1 450	1,081
	6,0	2,0	1,5	1 450	1,027
	9,0	2,0	1,5	1 450	1,107
	12,0	2,0	1,5	1 450	1,079
	3,0	3,7	2,5	2 550	1,142
	6,0	3,7	2,5	2 550	1,033
	9,0	3,7	2,5	2 550	1,090
	12,0	3,7	2,5	2 550	1,093
	3,0	5,3	4,0	3 800	1,092
	6,0	5,3	4,0	3 800	1,003
	9,0	5,3	4,0	3 800	1,045
	12,0	5,3	4,0	3 800	1,049
	3,0	7,0	5,0	5 310	1,024
	6,0	7,0	5,0	5 310	0,974
	9,0	7,0	5,0	5 310	1,015
	12,0	7,0	5,0	5 310	0,999
					1,053 mean

TESTS 129-160 (19mm flute 1,2m deep)	NOMINAL WATER FLOW (kg/s)	NOMINAL AIR FLOW (kg/s)	NOMINAL AIR VELOCITY (m/s)	NOMINAL REYNOLD NUMBER	Nu.A Cold/Hot
	3,0	2,0	1,5	1 450	0,890
	6,0	2,0	1,5	1 450	1,061
	9,0	2,0	1,5	1 450	0,995
	12,0	2,0	1,5	1 450	1,098
	3,0	3,7	2,5	2 550	0,907
	6,0	3,7	2,5	2 550	1,051
	9,0	3,7	2,5	2 550	1,035
	12,0	3,7	2,5	2 550	0,998
	3,0	5,3	4,0	3 800	0,903
	6,0	5,3	4,0	3 800	1,036
	9,0	5,3	4,0	3 800	1,029
	12,0	5,3	4,0	3 800	0,974
	3,0	7,0	5,0	5 310	0,985
	6,0	7,0	5,0	5 310	1,081
	9,0	7,0	5,0	5 310	1,174
	12,0	7,0	5,0	5 310	1,096
					1,020 mean

Table J.3 Ratio of Nu.A $_{cold/hot}$ for corresponding flow situations.

	Temperature			
	0°C	10°C	40°C	50°C
Density (kg/m^3)	998	997	992	998
Viscosity (Ns/m^2)	1752	1300	651	544
Surface tension ($x10^{-3}Nm$)	7,6	7,4	7,0	6,9

Note that the typical cold and hot water temperatures in the tests were 10°C and 40°C respectively.

Table J.4 Physical properties of water related to the formation of wet surface area

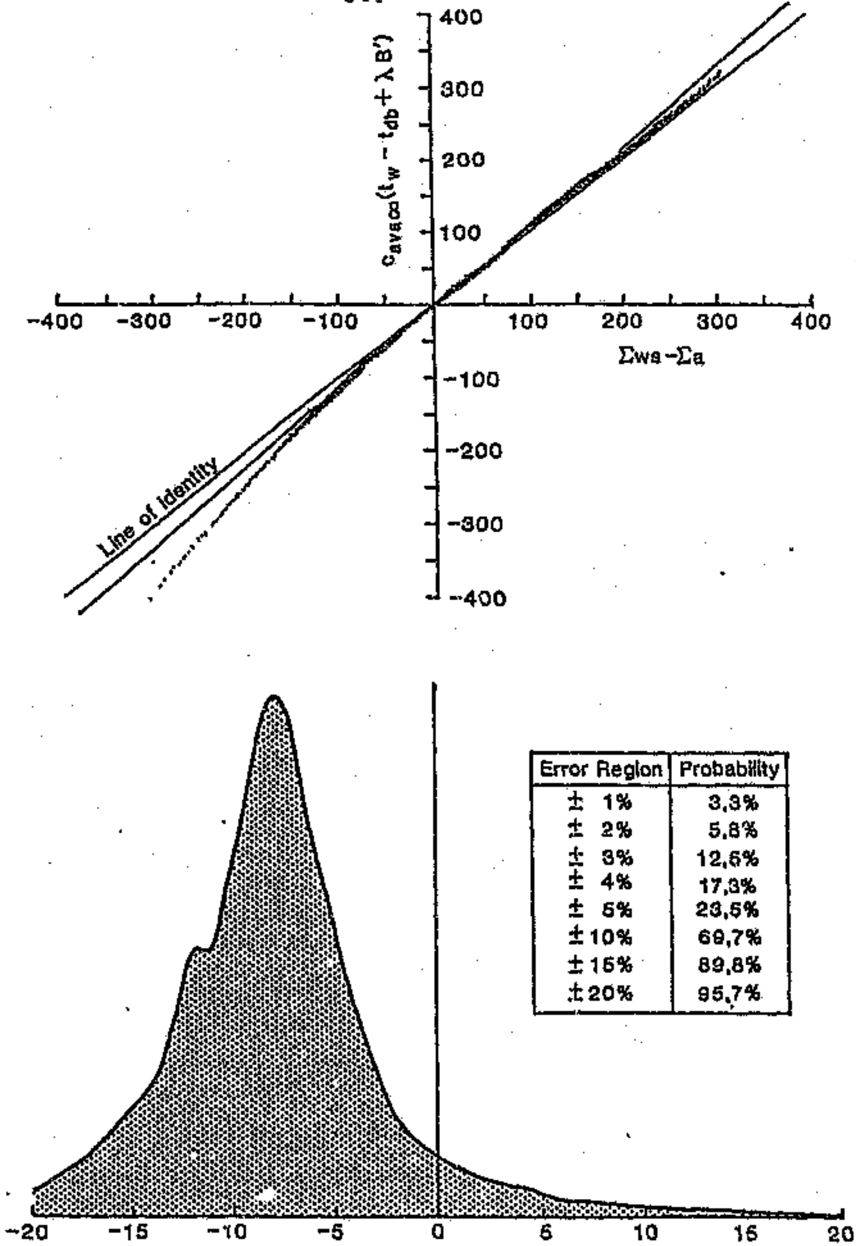
APPENDIX K ACCURACY OF MERKEL'S EQUATION WHEN USING SIGMA HEAT IN PLACE OF ENTHALPY

The exact equivalent of Merkel's equation when using sigma energy in place of enthalpy is given as:

$$\dot{q}''_t = \left(\frac{h_c}{C_{sva\infty}} \right) \left[\Sigma_w - \Sigma_\infty \right] \qquad (K.1)$$

In the same way that the accuracy of Merkel's equation was investigated in Section 6.4 the accuracy of this above equation has been examined.

The results are presented in the form of a correlation curve between the value of the sigma heat difference driving force and that of the true value as calculated from heat and mass transfer parameters. This plot is shown in Figure K.1 which gives an indication of the extent of the errors involved and their distribution (as a percentage of the true value). This figure should be compared to Figure 6.9 which is the equivalent figure used in the examination of the original Merkel equation. A close study will show that the sigma heat driving force equation is a slight improvement over the Merkel equation in terms of accuracy.



Error Region	Probability
± 1%	3,3%
± 2%	5,8%
± 3%	12,5%
± 4%	17,3%
± 5%	23,5%
±10%	69,7%
±15%	89,8%
±20%	95,7%

Figure K.1 Accuracy of Merkel's equation when using sigma energy in place of enthalpy (correlation and distribution of error)

APPENDIX L PROCEDURE FOR CALCULATING β AND ITS VALUE FOR NON-SATURATED AIR CONDITIONS

The term, β, is defined for a specific set of conditions, through Equation 7.11, as:

$$\beta = \frac{c_{avaf^*} (t_w - t_{db} + \lambda B')}{(\Sigma_w - \Sigma_\infty)} \tag{L.1}$$

The value of β is dependant on the air condition, the water surface temperature and the barometric pressure. Because of the complexity of the form of the equations involved it is not possible to express the term as a simple analytical function. It is however simple to numerically calculate its value for a particular set of conditions and a short program listing specifying the procedure is given below.

Values of β for saturated air conditions are presented in the main text. Figures L.1 and L.2 below give values for non-saturated conditiors.

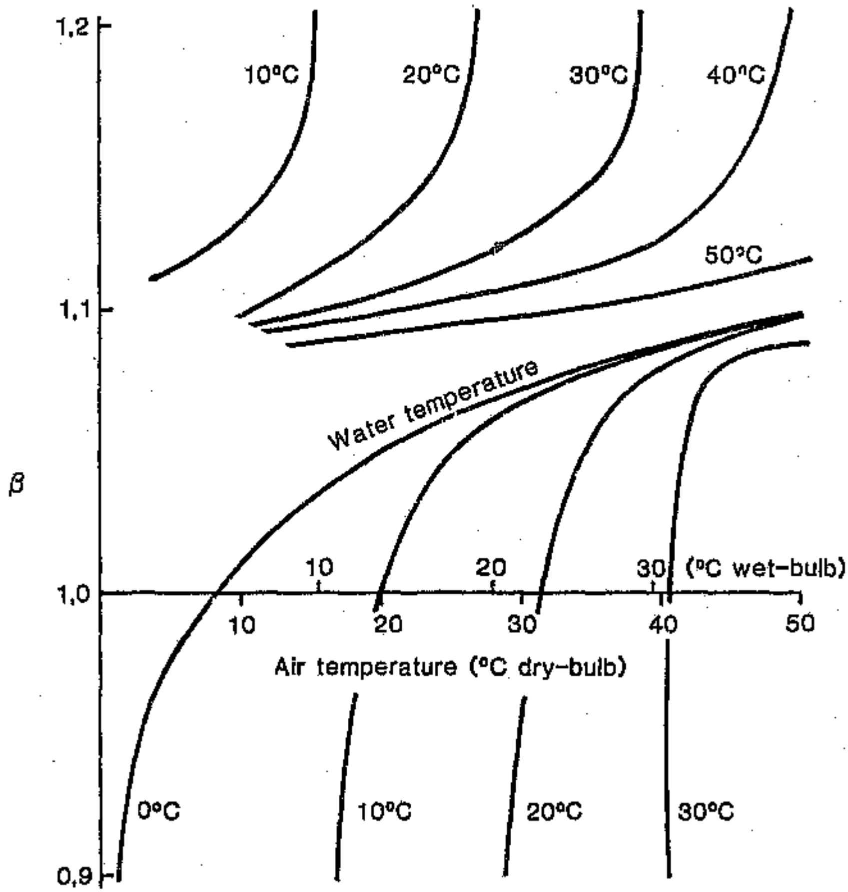


Figure L.1 Value of β for 50 per cent relative humidity air at 100 kPa

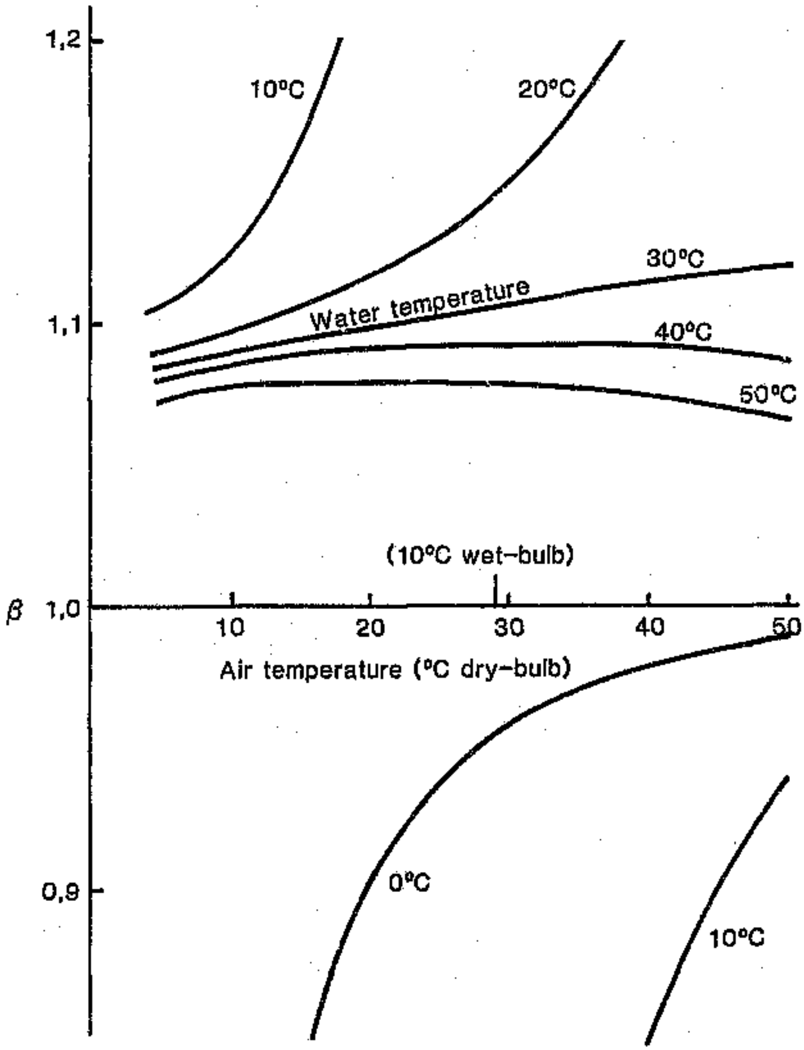


Figure L.2 Value of β for dry air at 100 kPa

```
10 ! PROGRAM - BETA
20 ! PROGRAM TO CALC VALUE OF B
   ETA
30 T1=30 ! Twater
40 T2=0 ! Tdb
50 T3=0 ! Twb
60 P=100 ! Pressure
70 T4=(T1+T2)/2 ! Tfilm
80 T5=(T1+T3)/2 ! Tfilm*
90 E1=.6105*EXP(17.27*T1/(237.3
   +T1)) ! SAT VAP PRESS Tws
100 E9=.6105*EXP(17.27*T3/(237.3
   +T3))
110 E2=(E9*(1555.6-2.465*T3+1.00
   5*T2)-P*1.005*(T2-T3))/(1555
   .6+.139*T2-1.599*T3-E9*.14*(
   T2-T3)/P)
120 ! VAP PRESS AIR
130 M1=.622*E1/(P-.378*E1) ! TSH
   ws
140 M2=.622*E2/(P-.378*E2) ! TSH
   air
150 L=2501-2.378*T1 ! LAT HEAT
160 E4=.6105*EXP(17.27*T4/(237.3
   +T4)) ! SAT VAP PRESS FILM
170 E5=.6105*EXP(17.27*T5/(237.3
   +T5)) ! SAT VAP PRESS FILM*
180 A4=.622*E4/(P-E4) ! FILM ASH
190 K=(2405+7 788*T4)*10^-5 ! FI
   LM CONDUCTIVITY
200 D=1.676*10^-7*(T4+273.15)^1
   694/P ! FILM DIFFUSIVITY
210 C=(1 005+1.84*A4)*(P-E4)/(P-
   .378*E4) ! FILM Cp
220 R=(P-.378*E4)/(.287*(273.15+
   T4)) ! FILM DENSITY
230 X=(C*1000*R*D/K)^(2/3) ! Lew
   is No
240 B=LOG((1-M2)/(1-M1)) ! MASS
   TRANS DRIVE FORCE
250 Q=X*L*B/C+T1-T2
260 A1=.622*E1/(P-E1) ! ASH Tws
270 A2=.622*E2/(P-E2) ! ASH AIR
280 S1=1.005*T1+(2501+1.84*T1)*A
   1-4.187*A1*T1 ! SIGMA Tws
300 S2=1.005*T2+(2501+1.84*T2)*A
   2-4.187*A2*T3 ! SIGMA air
320 A5= 622*E5/(P-E5) ! ASHfilm*
330 C5=1 005+1.84*A5 ! Cp film*
340 G=C5*Q/(S1-S2) ! BETA
350 PRINT "HEAT TRANSFER FROM WE
   T SURFACE, VALUE OF BETA"
360 PRINT ""
370 PRINT "T dry bulb=";T2
380 PRINT "T wet bulb=";T3
390 PRINT "T water surface=";T1
400 PRINT "Ambient pressure=";P
410 PRINT "BETA  =";G
430 PRINT ""
440 END
```

APPENDIX M Procedure for calculating the term α, and its value for non-saturated conditions

The term, α, for a differential element of direct-contact heat exchanger is defined by:

$$\ddot{q}_a = \dot{m}_a \, di_a = \alpha \, \dot{m}_a \, d\Sigma \qquad (M.1)$$

The value of α is dependant on the air condition, the water surface temperature and the barometric pressure. Because of the complexity of the form of the equations involved, it is not possible to express the term as a simple analytical function. It is however, a relatively simple matter to numerically calculate its value for a particular set of conditions. The short program listing given below specifies the exact procedure used.

Values of α for saturated air conditions are presented in the main text. Figures M.1 and M.2 below give the values for non-saturated conditions at 100 kPa.

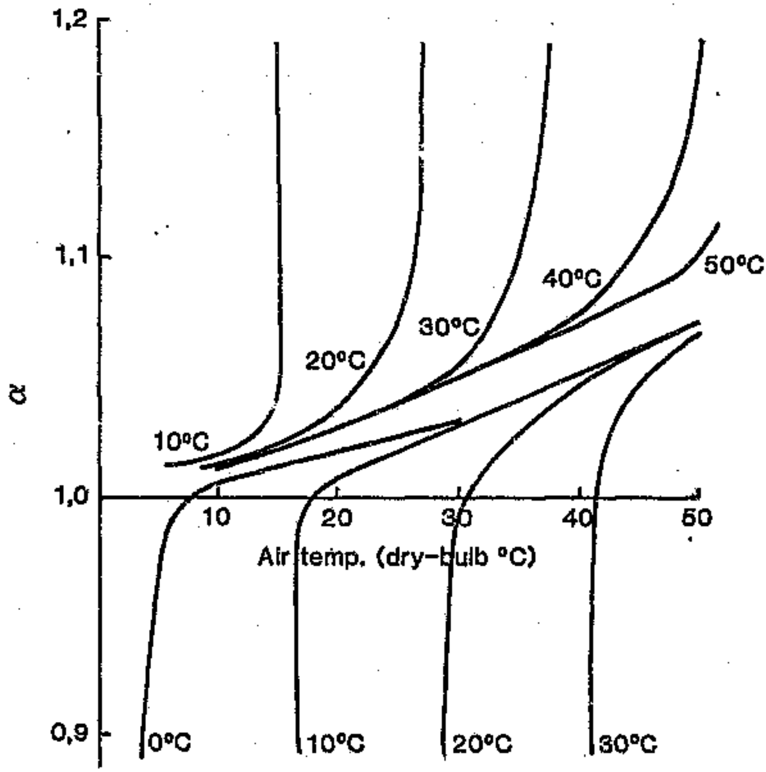


Figure M.1 Value of α for 50 per cent relative humidity air at 100 kPa

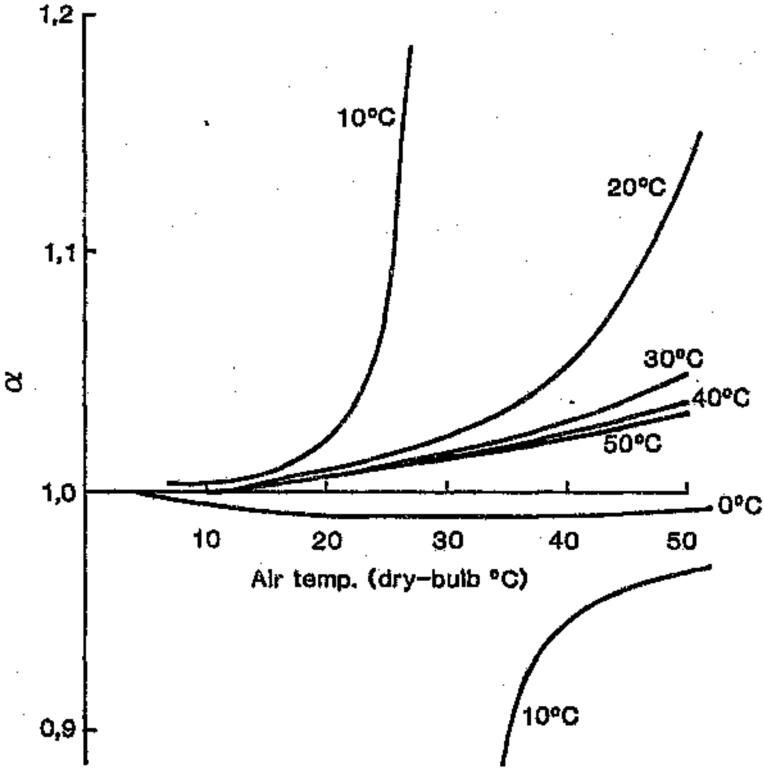


Figure M.2 Value of α for dry air at 100 kPa

```
 10 ! PROGRAM - ALPHA
 20 ! PROGRAM TO CALC ALPHA (WHE
    N FOG OCCURS AIR IS FORCED T
    O REMAIN SATURATED
 30 T1=40 ! Twater
 40 T2=50 ! Tdb
 50 T3=17.982 ! Twb
 60 P=100 ! Pressure
 70 Y=10^-8 ! hcA/Ma
 80 ! CALC OF HEAT @ MASS TRANS
 90 T4=(T1+T2)/2 ! Tfilm
100 E1=.6105*EXP(17.27*T1/(237.3
    +T1)) ! SAT VAP PRESS AT Tws
110 E9=.6105*EXP(17.27*T3/(237.3
    +T3))
120 E2=(E9*(1555.6-2.465*T3+1.00
    5*T2)-P*1.005*(T2-T3))/(1555
    .6+.139*T2-1.599*T3-E9*.14*(
    T2-T3)/P)
130 ! E2=VAP PRESS AIR
140 M1=.622*E1/(P-.378*E1) ! TSH
     WATER SURFACE

150 M2=.622*E2/(P-.378*E2) ! TSH
    AIR

160 L=2501-2.378*T1 ! LATENT HEA
    T
170 E4=.6105*EXP(17.27*T4/(237.3
    +T4)) ! VAP PRESS FILM
180 A4=.622*E4/(P-E4) ! ASH FILM
190 K=(2405+7.788*T4)*10^-5 ! CO
    NDUCTIVITY FILM

200 D=1.676*10^-7*(T4+273.15)^1.
    694/P ! DIFFUSIVITY FILM
210 C=(1.005+1.84*A4)*(P-E4)/(P-
    .378*E4) ! Cp FILM
220 R=(P-.378*E4)/(.287*(273.15+
    T4)) ! DENSITY FILM
230 X=(C*1000*R*D/K)^(2/3) ! Lew
    is No
240 B=LOG((1-M2)/(1-M1)) ! MASS
    TRANS DRIVE FORCE
250 Q=X*L*B/C+T1-T2 ! TOTAL HEAT
     TRANS DRIVE FORCE
260 Z=Q*Y ! TOTAL ENERGY TRANS
270 ! CALC OF NEW CONDITIONS- NO
     SUPER SATURATION
280 A2=.622*E2/(P-E2) ! ASH BEFO
    RE

290 H2=1.005*T2+(2501+1.84*T2)*A
    2 ! ENTHALPY BEFORE
300 S2=H2-4.187*A2*T3 ! SIGMA BE
    FORE
310 IF T3=T2 THEN GOTO 470 ! FOG
     CREATED BY SAT CONDITIONS,
    THE AIR IS NOT ALLOWED TO FO
    G
```

```
320 H9=H2+Z ! ENTHALPY AFTER
330 A9=A2+Y*X*B/C ! ASH AFTER
340 T9=(H9-2501*A9)/(1.005+1.84*
    A9) ! Tdb AFTER
350 E0=A9*P/(.622+A9) ! VAP PRES
    S AFTER
360 Z9=T3 ! 1ST Twb GUESS
370 Z8=.6105*EXP(17.27*Z9/(237.3
    +Z9)) ! SAT VAP PRESS AT Twb
380 Z7=(Z8*(1555.6-2.465*Z9+1.00
    5*T9)-P*1.005*(T9-Z9))/(1555
    .6+.139*T9-1.599*Z9-Z8*.14*(
    T9-Z9)/P)
390 ! Z7=VAP PRESS AS FUNC OF Tw
    b
400 IF ABS(Z7-E0)<10^-10 THEN GO
    TO 430
410 X1=Z8*4098/(237.3+Z9)^2+.064
     ! VAP PRESS;Twb DERIVITIVE
420 Z9=Z9-(Z7-E0)/X1 @ GOTO 370
430 S9=H9-4.187*A9*Z9 ! SIGMA AF
    TET
440 " Z/(S9-S2) ! ALPHA
    GOTO 530
460 ! CALC TO CATER FOR FOGGING
470 T=T2+.0001 ! SMALL INCREASE
    IN SAT TEMP

480 E=.6105*EXP(17.27*T/(237.3+T
    ))
490 A=.622*E/(P-E)
500 H=1.005*T+(2501+1.84*T)*A
510 S=H-4.187*A*T
520 U=(H2-H)/(S2-S) ! ALPHA
530 PRINT "HEAT TRANSFER FROM WE
    T SURFACE"
540 PRINT "VALUE OF ALPHA"
550 PRINT ""
560 PRINT "T dry bulb=";T2
570 PRINT "T wet bulb=";T3
580 PRINT "T water surface=";T1
590 PRINT "Ambient pressure=";P
600 PRINT "ALPHA =";U
610 PRINT ""
620 END
```

APPENDIX N Procedure for calculating the term, γ, and its value for non-saturated conditions

Recall from the main text that γ is defined through the following equations:

$$\dot{q}_w = \dot{m}_{wi} c_w (t_{wi} - t_{wo}) + d\dot{m}_w c_w t_{wo} \quad (N.1)$$

$$\dot{q}_w = \gamma \dot{m}_{wi} c_w (t_{wi} - t_{wo}) \quad (N.2)$$

Combining these two equations gives:

$$\gamma = 1 + (\Delta\dot{m}_w/\dot{m}_{wi}).(t_{wo}/\Delta t_w) \quad (N.3)$$

Note this equation applies irrespective of any fogging that may occur.

Alternatively, the formulations for the heat and mass transfer (from Chapter 2) may be substituted into Equation N.3 resulting in:

$$\gamma = 1 + \frac{B' c_w t_w}{(t_w - t_{db} + \lambda B' - c_w t_w B')} \quad (N.4)$$

The value of this equation can be determined numerically from a knowledge of the air condition, barometric pressure and the water temperature The routine used for this is listed below.

Values of this term for saturated conditions are given in the main text and values for non-saturated conditions at 100 kPa are given in Figures N.1 and N.2 below.

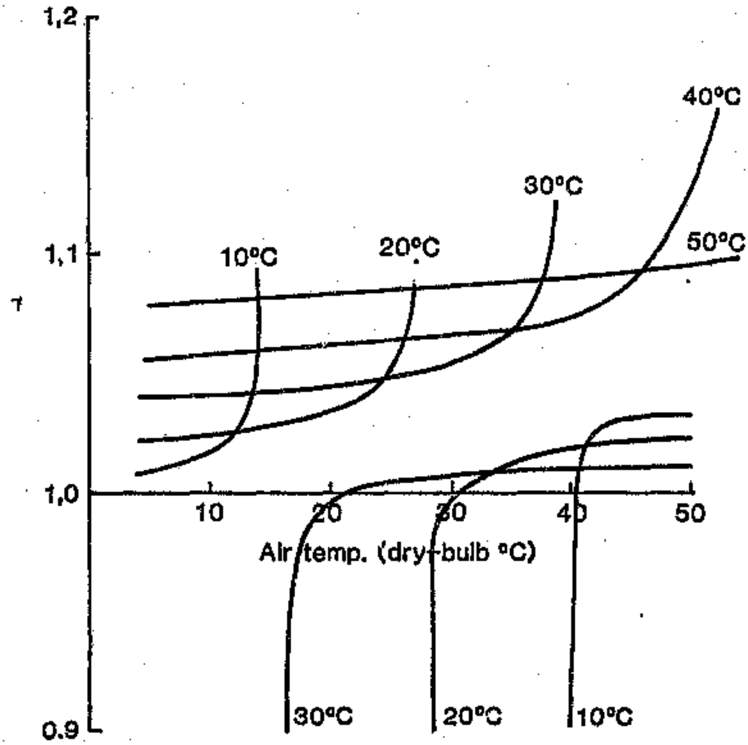


Figure N.1 Value of γ for 50 per cent relative humidity air at 100 kPa

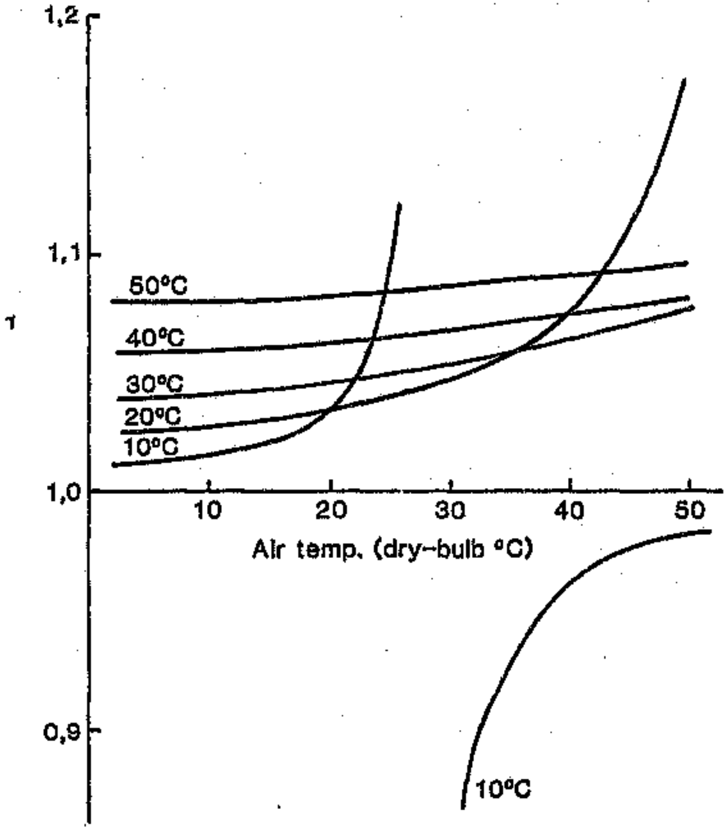


Figure N.2 Value of γ for dry air at 100 kPa

```
 10 ! PROGRAM GAMMA
 20 ! PROGRAM TO CALC GAMMA, NOT
     EFFECTED BY FOGGING
 30 T1=10 ! Twater
 40 T2=30 ! Tdb
 50 T3=30 ! Twb
 60 A=1 ! Ma kg/s
 70 W=1 ! Mw l/s
 80 J=.001 ! hcA/Ma
 90 P=100 ! Pressure
100 H=J*A ! hcA
110 T4=(T1+T2)/2 ! Tfilm
120 E1=.6105*EXP(17.27*T1/(237.3
    +T1)) ! SAT VAP PRESS AT Tws
130 E9=.6105*EXP(17.27*T3/(237.3
    +T3)) ! SAT VAP PRESS AT Twb
140 E2=(E9*(1555.6-2.465*T3+1.00
    5*T2)-P*1.005*(T2-T3))/(1555
    .6+.139*T2-1.599*T3-E9*.14*(
    T2-T3)/P)
150 ! E2=VAP PRESS AIR IN
160 M1=.622*E1/(P-.378*E1) ! TSH
    ws
170 M2=.622*E2/(P-.378*E2) ! TSH
    air
180 L=2501-2.378*T1 ! LATENTHEAT
190 E4=.6105*EXP(17.27*T4/(237.3
    +T4)) ! FILM VAP PRESS
200 A4=.622*E4/(P-E4) ! FILM ASH
210 K=(2405+7.788*T4)*10^-5 ! Fi
    lm conductivity
220 D=1.676*10^-7*(T4+273.15)^1.
    694/P ! FILM DIFFUSIVITY
230 C=(1.005+1.84*A4)*(P-E4)/(P-
    .378*E4) ! FILM Cp
240 R=(P-.378*E4)/(.287*(273.15+
    T4)) ! FILM DENSITY
250 X=(C*1000*R*D/K)^(2/3) ! Le
260 B=LOG((1-M2)/(1-M1)) ! Mass
    trans drive force
270 Q=H*(X*L*B/C+T1-T2) ! TOTAL
    ENERGY TRANS
280 M=H*X*B/C ! MASS TRANS kg/s
290 B9=X*B/C ! B'=Mt/hcA
300 T8=(W*T1-Q/4.187)/(W-M) ! Tw
    out
310 G=1+M*T1/(W*(T1-T8))
320 ! ALTERNATE METHOD
330 G1=1+B9*4.187*T1/(T1-T2+L*B9
    -B9*4.187*T1)
340 PRINT "HEAT TRANSFER FROM WE
    T SURFACE VALUE OF GAMMA"
360 PRINT "T dry bulb=";T2
370 PRINT "T wet bulb=";T3
380 PRINT "T water surface=";T1
390 PRINT "Ambient pressure=";P
400 PRINT "GAMMA";G;G1
430 END
```

APPENDIX O Mathematical manipulation to produce performance equation for direct-contact case

In the main text the following equation is developed.

$$\frac{h_c \, dA}{\dot{m}_a(\alpha/\beta)c_{avaf^*}} = \frac{d\Sigma}{J_3 + J_4 \Sigma} \qquad (0.1)$$

where

$$J_3 = a + c^*_{aw} t_{wo} - \frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} \Sigma_i$$

$$J_4 = \frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} - 1$$

This appendix details the mathematical manipulation required to solve this integral and to express the solution in a suitable form.

Integrating both sides of Equation 0.1 and using representative mean values of $[(\alpha/\beta)c_{avaf^*}]$, c^*_{aw} and $(\alpha/\gamma)_i$ produces:

$$\frac{h_c A}{\dot{m}_a(\alpha/\beta)c_{avaf^*}} = \frac{1}{J_4} [\ln (J_3 + J_4 \Sigma_o) - \ln (J_3 + J_4 \Sigma_i)] \qquad (0.2)$$

which becomes:

$$\frac{J_3 + J_4 \Sigma_o}{J_3 + J_4 \Sigma_i} = e^{[\frac{J_4 h_c A}{\dot{m}_a(\alpha/\beta)c_{avaf^*}}]} \qquad (0.3)$$

An overall heat balance across the heat exchanger produces (see Equation 7.49 Chapter 7):

$$\Sigma_o = \Sigma_i + \frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a} (t_{wi} - t_{wo}) \qquad (0.4)$$

Substituting J_3, J_4 and Σ_o into Equation 0.3 produces the following for the numerator on the lefthand side:

$$a + c^*_{aw} t_{wo} - \frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} \Sigma_i + [\frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} - 1][\Sigma_i + \frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a} (t_{wi} - t_{wo})] \qquad (0.5)$$
$$- c^*_{aw} [\frac{a}{c^*_{aw}} + t_{wo} - \frac{\Sigma_i}{c^*_{aw}} + \frac{\alpha_i}{\gamma_i} \frac{\gamma_o}{\alpha_o} (t_{wi} - t_{wo}) - \frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a c^*_{aw}} (t_{wi} - t_{wo})]$$

Similarly, the denominator on the lefthand side becomes:

$$a + c^*_{aw} t_{wo} - \frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} \Sigma_i + \frac{\alpha_i}{\gamma_i} \frac{\dot{m}_a c^*_{aw}}{\dot{m}_w c_w} \Sigma_i - \Sigma_i \qquad (0.6)$$
$$= a + c^*_{aw} t_{wo} - \Sigma_i$$

Equation 0.3 may then be written as:

$$a/c^*_{aw} + t_{wo} - \Sigma_i/c^*_{aw} + \frac{\alpha_i}{\gamma_i} \frac{\gamma_o}{\alpha_o} (t_{wi} - t_{wo}) - \frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a c^*_{aw}} (t_{wi} - t_{wo}) \qquad (0.7)$$
$$= (a/c^*_{aw} + t_{wo} - \Sigma_i/c^*_{aw}) \, e^{[\frac{J_4 h_c A}{\dot{m}_a c_{aval} \cdot (\alpha/\beta)}]}$$

Solving for t_{wo} gives:

$$t_{wo} = \frac{t_{wi} (\frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a c^*_{aw}} - \frac{\alpha_i}{\gamma_i} \frac{\gamma_o}{\alpha_o}) + [(\Sigma_i - a)/c^*_{aw}][1 - e^{[-\frac{J_4 h_c A}{\dot{m}_a c_{aval} \cdot (\alpha/\beta)}]}]}{1 - \frac{\alpha_i}{\gamma_i} \frac{\gamma_o}{\alpha_o} + \frac{\gamma_o}{\alpha_o} \frac{\dot{m}_w c_w}{\dot{m}_a c^*_{aw}} - e^{(\frac{J_4 h_c A}{\dot{m}_a c_{aval} \cdot (\alpha/\beta)})}} \qquad (0.8)$$

The water efficiency is given as:

$$E_w = (t_{wi} - t_{wo})/(t_{wi} - t_{ai}) \qquad (0.9)$$

Substituting for t_{wo} gives:

$$E_w = \frac{[t_{wi} - (\Sigma_i - a)/c^*_{aw}]\,[1 - e^{[\frac{J_4\, h_c A}{m'_a C_{aval}(\alpha/\beta)}]}]}{[t_{wi} - t_{ai}]\,[1 - \frac{\alpha_i}{\eta_i}\frac{\gamma_o}{\alpha_o} + \frac{\gamma_o}{\alpha_o}\frac{m'_w C_w}{m'_a C^*_{aw}} - e^{[\frac{J_4\, h_c A}{m'_a C_{aval}(\alpha/\beta)}]}]} \qquad (0.10)$$

Substituting for J_4 gives:

$$E_w = \frac{(t_{wi} - (\Sigma_i - a)/c^*_{aw}]\,[1 - e^{-(\frac{h_c A}{m'_a C_{aval}(\alpha/\beta)})(1 - \frac{\alpha_i}{\eta_i}\frac{m'_a C^*_{aw}}{m'_w C_w})}]}{[t_{wi} - t_{ai}]\,[1 - \frac{\alpha_i}{\eta_i}\frac{\eta_i}{\alpha_o} + \frac{\gamma_o}{\alpha_o}\frac{m'_w C_w}{m'_a C^*_{aw}} - e^{-(\frac{h_c A}{m'_a C_{aval}(\alpha/\beta)})(1 - \frac{\alpha_i}{\eta_i}\frac{m'_a C^*_{aw}}{m'_w C_w})}]} \qquad (0.11)$$

Rearranging allows this to be written as:

$$\frac{t_{wi} - t_{wo}}{t_{wi} - (\frac{\Sigma_i - a}{C^*_{aw}})} = \frac{1 - e^{-(\frac{h_c A}{m'_a C_{aval}(\alpha/\beta)})(1 - \frac{\alpha_i}{\eta}\frac{m'_a C^*_{aw}}{m'_w C_w})}}{(1 - \frac{\alpha_i}{\eta_i}\frac{\gamma_o}{\alpha_o} + \frac{\gamma_o}{\alpha_o}\frac{m'_w C_w}{m'_a C^*_{aw}} - e^{-(\frac{h_c A}{m'_a C_{aval}(\alpha/\beta)})(1 - \frac{\alpha_i}{\eta_i}\frac{m'_a C^*_{aw}}{m'_w C_w})}]} \qquad (0.12)$$

It must be noted that the lefthand side term can also be expressed as:

$$\frac{t_{wi} - t_{wo}}{t_{wi} - \frac{\Sigma_i - a}{C^*_{aw}}} = \frac{t_{wi} - t_{wo}}{t_{wi} - \frac{C^*_{ai}}{C^*_{aw}}\, t_{ai}} \qquad (0.13)$$

The term, c^*_{ai}, is the pseudo-specific heat term for saturated air at the air inlet condition.

Finally, the equation can be written in a simpler format by introducing various groupings of terms which, as discussed in the main text, are analogous to the so called heat exchanger terms used for conventional heat exchangers (with the exception of the term, J).

$$E_w^* = \frac{1 - e^{-N^*(1 - 1/R^*)}}{(1 - J + JR^*) - e^{-N^*(1 - 1/R^*)}} \qquad (0.14)$$

where

$R^* = [\, \dot{m}_w c_w \,]/[\, \dot{m}_a c^*_{aw} (\alpha/\gamma)_i \,]$

$N^* = h_c A \,/\, [\, \dot{m}_a (\alpha/\beta)\, c_{avel^*} \,]$

$E_w^* = (\, t_{wi} - t_{wo} \,)/(\, t_{wi} - (\, \frac{c^*_{ai}}{c^*_{aw}} \,)\, t_{wbi} \,)$

$J = (\alpha/\gamma)_i \,/\, (\alpha/\gamma)_o$

APPENDIX P Generation of simulated database.

In order to supplement the experimental database a large number of test simulations were carried out. The computer simulator was run for a wide variety of flow conditions for heat exchangers with widely differing design characteristics over the full range of temperature conditions.

The heat and mass transfer conditions were simulated for water-air flow ratios of 0,75; 2,0 and 4,0; for a range of heat exchangers with design characteristic values of N* = 1,0; 2,5 and 4,0; for barometric pressures of 80; 100 and 120 kPa; and air and water inlet temperature conditions as shown in Table P.1. Unrealistic operating duties for water efficiencies less than 0,075 or greater than 0,925 were subsequently deleted from this set of data. This amounted to a total of more than 490 sets of conditions. This database is recorded in the following tables.

Inlet water temperature (°C)

Inlet wet-bulb temperature (°C)	0	5	10	15	20	25	30	35	40	45	50
0											
5				★		★		★		★	
10											
15		★				★		★		★	
20											
25		★		★				★		★	
30											
35		★		★		★				★	
40											
45		★		★		★		★			
50											

Table P.1 Inlet temperature conditions used in generating simulated data base

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
80.0	.75	1.00	1.00	5.00	9.63	15.00	10.02	-14.79	-3.83
80.0	.75	1.00	1.00	5.00	16.37	25.00	16.40	-36.37	-10.79
80.0	.75	1.00	1.00	5.00	26.01	35.00	24.39	-68.39	-22.31
80.0	.75	1.00	1.00	5.00	38.96	45.00	34.40	-112.97	-39.25
80.0	.75	1.00	1.00	15.00	10.60	5.00	10.58	13.81	3.23
80.0	.75	1.00	1.00	15.00	21.23	25.00	20.64	-20.16	-6.22
80.0	.75	1.00	1.00	15.00	30.05	35.00	27.94	-49.25	-16.41
80.0	.75	1.00	1.00	15.00	41.53	45.00	37.21	-88.86	-31.52
80.0	.75	1.00	1.00	25.00	15.15	5.00	16.24	31.27	7.84
80.0	.75	1.00	1.00	25.00	19.23	15.00	20.03	18.39	5.21
80.0	.75	1.00	1.00	25.00	33.00	35.00	31.53	-26.34	-9.08
80.0	.75	1.00	1.00	25.00	43.26	45.00	39.97	-61.45	-22.30
80.0	.75	1.00	1.00	35.00	18.56	5.00	21.70	52.55	13.99
80.0	.75	1.00	1.00	35.00	22.36	15.00	24.92	40.60	11.96
80.0	.75	1.00	1.00	35.00	27.67	25.00	29.21	23.75	7.56
80.0	.75	1.00	1.00	45.00	20.93	5.00	26.73	77.36	21.66
80.0	.75	1.00	1.00	45.00	24.49	15.00	29.47	66.49	20.19
80.0	.75	1.00	1.00	45.00	29.45	25.00	33.16	50.80	16.40
80.0	.75	1.00	1.00	45.00	36.26	35.00	38.21	28.81	9.04
100.0	.75	1.00	1.00	5.00	9.13	15.00	9.86	-13.15	-3.13
100.0	.75	1.00	1.00	5.00	15.02	25.00	15.92	-31.94	-8.88
100.0	.75	1.00	1.00	5.00	23.44	35.00	23.43	-59.60	-18.58
100.0	.75	1.00	1.00	5.00	35.22	45.00	32.69	-99.82	-33.56
100.0	.75	1.00	1.00	15.00	11.04	5.00	10.70	12.42	2.63
100.0	.75	1.00	1.00	15.00	20.51	25.00	20.37	-17.78	-5.16
100.0	.75	1.00	1.00	15.00	28.36	35.00	27.21	-43.45	-13.79
100.0	.75	1.00	1.00	15.00	39.03	45.00	35.00	-79.86	-27.24
100.0	.75	1.00	1.00	25.00	16.14	5.00	16.56	28.12	6.47
100.0	.75	1.00	1.00	25.00	19.85	15.00	20.26	16.43	4.35
100.0	.75	1.00	1.00	25.00	32.19	35.00	31.12	-23.59	-7.80
100.0	.75	1.00	1.00	25.00	41.82	45.00	38.97	-56.38	-19.78
100.0	.75	1.00	1.00	35.00	20.15	5.00	22.32	47.46	11.75
100.0	.75	1.00	1.00	35.00	23.61	15.00	25.40	36.61	10.16
100.0	.75	1.00	1.00	35.00	28.38	25.00	29.58	21.42	6.52
100.0	.75	1.00	1.00	35.00	43.76	45.00	42.09	-29.32	-10.55
100.0	.75	1.00	1.00	45.00	23.10	5.00	27.74	70.45	18.56
100.0	.75	1.00	1.00	45.00	26.33	15.00	30.41	60.42	17.45
100.0	.75	1.00	1.00	45.00	30.78	25.00	33.94	46.39	14.46
100.0	.75	1.00	1.00	45.00	36.96	35.00	38.60	26.64	8.83
120.0	.75	1.00	1.00	5.00	8.78	15.00	9.75	-12.02	-2.64
120.0	.75	1.00	1.00	5.00	14.06	25.00	15.59	-28.83	-7.54
120.0	.75	1.00	1.00	5.00	21.56	35.00	22.76	-53.36	-15.86
120.0	.75	1.00	1.00	5.00	32.15	45.00	31.50	-89.25	-29.05
120.0	.75	1.00	1.00	15.00	11.35	5.00	10.77	11.45	2.22
120.0	.75	1.00	1.00	15.00	19.98	25.00	20.10	-16.06	-4.48
120.0	.75	1.00	1.00	15.00	27.04	35.00	26.69	-39.10	-11.88
120.0	.75	1.00	1.00	15.00	36.81	45.00	34.79	-72.23	-23.76
120.0	.75	1.00	1.00	25.00	16.85	5.00	16.76	25.82	5.49
120.0	.75	1.00	1.00	25.00	20.31	15.00	20.44	15.04	3.74
120.0	.75	1.00	1.00	25.00	31.34	35.00	30.82	-21.42	-6.80

Table P.2 Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
120.0	.75	1.00	1.00	25.00	40.48	45.00	38.24	-51.57	-17.51
120.0	.75	1.00	1.00	35.00	21.36	5.00	22.75	43.73	10.12
120.0	.75	1.00	1.00	35.00	24.59	15.00	25.88	33.61	8.02
120.0	.75	1.00	1.00	35.00	28.96	25.00	29.85	19.66	5.73
120.0	.75	1.00	1.00	35.00	43.16	45.00	41.69	-27.35	-9.57
120.0	.73	1.00	1.00	45.00	24.70	5.00	28.45	65.17	16.22
120.0	.75	1.00	1.00	45.00	27.80	15.00	31.11	55.79	15.38
120.0	.75	1.00	1.00	45.00	31.88	25.00	34.53	42.91	12.08
120.0	.75	1.00	1.00	45.00	37.48	35.00	39.04	24.85	7.99
80.0	.75	1.00	2.50	5.00	11.68	15.00	7.51	-21.23	-5.41
80.0	.75	1.00	2.50	5.00	21.01	25.00	11.50	-51.58	-14.85
80.0	.75	1.00	2.50	15.00	8.72	5.00	12.70	19.88	4.77
80.0	.75	1.00	2.50	15.00	23.56	25.00	18.77	-27.70	-8.44
80.0	.75	1.00	2.50	25.00	11.20	5.00	19.63	43.88	11.43
80.0	.75	1.00	2.50	25.00	17.09	15.00	21.68	25.36	7.28
80.0	.75	1.00	2.50	35.00	12.66	5.00	25.59	71.21	19.73
80.0	.75	1.00	2.50	35.00	18.26	15.00	27.35	53.79	16.09
80.0	.75	1.00	2.50	45.00	18.87	15.00	32.10	84.12	25.98
100.0	.75	1.00	2.50	5.00	10.99	15.00	7.22	-19.03	-4.43
100.0	.75	1.00	2.50	5.00	19.33	25.00	10.60	-45.99	-12.29
100.0	.75	1.00	2.50	5.00	30.71	35.00	16.34	-83.98	-25.27
100.0	.75	1.00	2.50	15.00	9.30	5.00	12.95	18.05	3.95
100.0	.75	1.00	2.50	15.00	22.70	25.00	18.17	-25.11	-7.18
100.0	.75	1.00	2.50	15.00	33.04	35.00	23.55	-59.23	-18.57
100.0	.75	1.00	2.50	25.00	12.39	5.00	20.29	46.11	9.69
100.0	.75	1.00	2.50	25.00	17.77	15.00	22.14	23.18	6.24
100.0	.75	1.00	2.50	35.00	14.36	5.00	26.75	65.86	17.17
100.0	.75	1.00	2.50	35.00	19.46	15.00	28.37	49.95	14.28
100.0	.75	1.00	2.50	35.00	26.27	25.00	30.88	28.37	8.69
100.0	.75	1.00	2.50	45.00	15.48	5.00	32.26	94.38	26.05
100.0	.75	1.00	2.50	45.00	20.41	15.00	33.66	79.24	23.45
100.0	.75	1.00	2.50	45.00	26.95	25.00	35.82	58.78	18.51
120.0	.75	1.00	2.50	5.00	10.51	15.00	7.05	-17.46	-3.74
120.0	.75	1.00	2.50	5.00	18.06	25.00	10.01	-41.80	-10.43
120.0	.75	1.00	2.50	5.00	28.52	35.00	14.75	-76.46	-21.74
120.0	.75	1.00	2.50	5.00	41.91	45.00	23.26	-122.71	-30.08
120.0	.75	1.00	2.50	15.00	9.72	5.00	13.11	16.71	3.36
120.0	.75	1.00	2.50	15.00	22.14	25.00	17.79	-22.99	-6.19
120.0	.75	1.00	2.50	15.00	31.70	35.00	22.30	-54.08	-16.37
120.0	.75	1.00	2.50	25.00	13.30	5.00	20.73	37.21	8.38
120.0	.75	1.00	2.50	25.00	18.31	15.00	22.45	21.43	5.44
120.0	.75	1.00	2.50	25.00	33.84	35.00	29.13	-29.05	-9.10
120.0	.75	1.00	2.50	35.00	15.72	5.00	27.57	61.53	15.19
120.0	.75	1.00	2.50	35.00	20.40	15.00	29.10	46.68	12.63
120.0	.75	1.00	2.50	35.00	26.70	25.00	31.37	26.70	7.86
120.0	.75	1.00	2.50	45.00	17.20	5.00	33.50	88.98	23.45
120.0	.75	1.00	2.50	45.00	21.77	15.00	34.83	74.09	21.30
120.0	.75	1.00	2.50	45.00	27.7Y	25.00	36.00	56.03	17.05
80.0	.75	1.00	4.00	5.00	12.47	15.00	6.45	-23.76	-5.99
80.0	.75	1.00	4.00	5.00	22.76	25.00	9.48	-57.33	-16.31

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
80.01	.75	1.00	4.00	15.00	7.96	5.00	13.49	22.29	5.40
80.01	.75	1.00	4.00	25.00	9.61	5.00	20.84	48.85	12.89
80.01	.75	1.00	4.00	25.00	16.29	15.00	22.25	27.91	8.04
80.01	.75	1.00	4.00	35.00	10.40	5.00	26.88	78.21	21.94
80.01	.75	1.00	4.00	35.00	16.86	15.00	28.12	58.20	17.51
80.01	.75	1.00	4.00	45.00	10.72	5.00	31.80	109.07	31.96
100.01	.75	1.00	4.00	5.00	11.69	15.00	6.16	-21.26	-4.88
100.01	.75	1.00	4.00	5.00	20.99	25.00	8.24	-51.39	-13.51
100.01	.75	1.00	4.00	15.00	8.60	5.00	13.78	20.25	4.49
100.01	.75	1.00	4.00	15.00	23.65	25.00	17.26	-27.95	-7.92
100.01	.75	1.00	4.00	25.00	10.85	5.00	21.64	44.94	11.04
100.01	.75	1.00	4.00	25.00	16.93	15.00	22.83	25.82	7.00
100.01	.75	1.00	4.00	35.00	12.04	5.00	28.20	73.00	19.37
100.01	.75	1.00	4.00	35.00	17.90	15.00	29.36	54.88	15.72
100.01	.75	1.00	4.00	45.00	12.59	5.00	33.74	103.31	28.93
100.01	.75	1.00	4.00	45.00	18.33	15.00	34.60	85.70	25.55
120.01	.75	1.00	4.00	5.00	11.14	15.00	6.00	-19.44	-4.10
120.01	.75	1.00	4.00	5.00	19.57	25.00	7.62	-46.65	-11.41
120.01	.75	1.00	4.00	5.00	31.14	35.00	10.94	-85.31	-23.71
120.01	.75	1.00	4.00	15.00	9.07	5.00	13.93	10.66	3.00
120.01	.75	1.00	4.00	15.00	22.99	25.00	16.79	-25.71	-6.85
120.01	.75	1.00	4.00	15.00	33.48	35.00	20.32	-60.95	-17.89
120.01	.75	1.00	4.00	25.00	11.83	5.00	22.14	41.73	9.58
120.01	.75	1.00	4.00	25.00	17.49	15.00	23.10	23.89	6.11
120.01	.75	1.00	4.00	35.00	13.42	5.00	29.27	68.70	17.27
120.01	.75	1.00	4.00	35.00	18.86	15.00	30.22	51.67	14.13
120.01	.75	1.00	4.00	35.00	26.00	25.00	31.80	29.18	8.61
120.01	.75	1.00	4.00	45.00	14.21	5.00	35.17	98.09	26.32
120.01	.75	1.00	4.00	45.00	19.53	15.00	36.04	81.79	23.49
80.01	2.00	1.00	1.00	5.00	6.95	15.00	9.35	-16.58	-4.27
80.01	2.00	1.00	1.00	5.00	9.93	25.00	14.90	-41.42	-12.18
80.01	2.00	1.00	1.00	5.00	14.44	35.00	21.81	-80.48	-26.00
80.01	2.00	1.00	1.00	5.00	21.51	45.00	30.25	-143.02	-49.25
80.01	2.00	1.00	1.00	15.00	13.07	5.00	11.36	15.98	3.77
80.01	2.00	1.00	1.00	15.00	17.79	25.00	19.66	-24.19	-7.38
80.01	2.00	1.00	1.00	15.00	22.11	35.00	25.69	-61.74	-20.24
80.01	2.00	1.00	1.00	15.00	28.87	45.00	33.35	-121.11	-42.04
80.01	2.00	1.00	1.00	25.00	20.49	5.00	18.18	38.25	9.88
80.01	2.00	1.00	1.00	25.00	22.30	15.00	21.10	22.88	6.53
80.01	2.00	1.00	1.00	25.00	29.05	35.00	30.15	-35.67	-12.15
80.01	2.00	1.00	1.00	25.00	35.31	45.00	36.92	-91.35	-32.66
80.01	2.00	1.00	1.00	35.00	26.97	5.00	25.17	69.03	19.04
80.01	2.00	1.00	1.00	35.00	28.67	15.00	27.49	54.57	16.34
80.01	2.00	1.00	1.00	35.00	31.19	25.00	30.66	33.06	10.60
80.01	2.00	1.00	1.00	35.00	40.78	45.00	40.89	-51.42	-18.82
80.01	2.00	1.00	1.00	45.00	32.30	5.00	31.98	110.35	32.38
80.01	2.00	1.00	1.00	45.00	33.89	15.00	33.82	96.97	30.27
80.01	2.00	1.00	1.00	45.00	36.22	25.00	36.37	77.03	25.34
80.01	2.00	1.00	1.00	45.00	39.72	35.00	39.96	46.56	15.98
100.01	2.00	1.00	1.00	5.00	6.71	15.00	9.27	-14.51	-3.43

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
100.01	2.00	[illegible]	1.00	5.00	9.25	25.00	14.63	-35.62	-9.81
100.01	2.00	[illegible]	[illegible]	5.00	13.01	35.00	21.26	-67.09	-20.92
100.01	2.00	[illegible]	[illegible]	5.00	18.76	45.00	29.30	-118.54	-39.48
100.01	2.00	[illegible]	[illegible]	15.00	13.33	5.00	11.41	14.15	3.03
100.01	2.00	1.00	1.00	15.00	17.38	25.00	19.52	-20.68	-5.93
100.01	2.00	1.00	1.00	15.00	21.05	35.00	25.33	-51.05	-16.28
100.01	2.00	1.00	1.00	15.00	26.55	45.00	32.55	-100.65	-33.83
100.01	2.00	1.00	1.00	25.00	21.07	5.00	18.28	33.43	7.87
100.01	2.00	1.00	1.00	25.00	22.69	15.00	21.22	19.80	5.29
100.01	2.00	1.00	1.00	25.00	28.46	35.00	29.95	-29.91	-9.78
100.01	2.00	1.00	1.00	25.00	33.68	45.00	36.33	-76.21	-26.28
100.01	2.00	1.00	1.00	35.00	28.04	5.00	25.42	59.98	15.40
100.01	2.00	1.00	1.00	35.00	29.57	15.00	27.77	47.01	13.29
100.01	2.00	1.00	1.00	35.00	31.73	25.00	30.83	28.11	8.61
100.01	2.00	1.00	1.00	35.00	39.89	45.00	40.54	-43.31	-15.40
100.01	2.00	1.00	1.00	45.00	33.98	5.00	32.49	95.74	26.49
100.01	2.00	1.00	1.00	45.00	35.42	15.00	34.35	83.62	24.88
100.01	2.00	1.00	1.00	45.00	37.46	25.00	36.84	66.04	20.99
100.01	2.00	1.00	1.00	45.00	40.48	35.00	40.27	39.78	13.25
120.01	2.00	1.00	1.00	5.00	6.56	15.00	9.22	-13.12	-2.87
120.01	2.00	1.00	1.00	5.00	8.72	25.00	14.39	-31.83	-8.24
120.01	2.00	1.00	1.00	5.00	12.02	35.00	20.83	-59.59	-17.55
120.01	2.00	1.00	1.00	5.00	16.96	45.00	28.61	-102.33	-32.98
120.01	2.00	1.00	1.00	15.00	13.48	5.00	11.42	12.85	2.52
120.01	2.00	1.00	1.00	15.00	17.11	25.00	19.43	-18.38	-4.96
120.01	2.00	1.00	1.00	15.00	20.29	35.00	25.05	-45.33	-13.65
120.01	2.00	1.00	1.00	15.00	25.01	45.00	32.06	-86.82	-28.31
120.01	2.00	1.00	1.00	25.00	21.40	5.00	18.33	30.13	6.56
120.01	2.00	1.00	1.00	25.00	22.94	15.00	21.28	17.65	4.42
120.01	2.00	1.00	1.00	25.00	28.00	35.00	29.78	-26.17	-8.22
120.01	2.00	1.00	1.00	25.00	32.55	45.00	35.93	-65.78	-21.96
120.01	2.00	1.00	1.00	35.00	28.76	5.00	25.52	53.55	12.85
120.01	2.00	1.00	1.00	35.00	30.17	15.00	27.91	41.65	11.15
120.01	2.00	1.00	1.00	35.00	32.12	25.00	30.96	24.75	7.26
120.01	2.00	1.00	1.00	35.00	39.26	45.00	40.30	-37.54	-12.99
120.01	2.00	1.00	1.00	45.00	35.17	5.00	32.79	85.32	22.32
120.01	2.00	1.00	1.00	45.00	36.50	15.00	34.68	74.05	21.03
120.01	2.00	1.00	1.00	45.00	38.35	25.00	37.15	58.19	17.75
120.01	2.00	1.00	1.00	45.00	41.02	35.00	40.48	34.08	11.28
80.01	2.00	1.00	2.50	5.00	7.85	15.00	6.34	-24.03	-6.04
80.01	2.00	1.00	2.50	5.00	12.07	25.00	8.26	-60.46	-17.04
80.01	2.00	1.00	2.50	5.00	18.67	35.00	11.33	-117.60	-36.39
80.01	2.00	1.00	2.50	5.00	29.03	45.00	16.34	-209.98	-69.82
80.01	2.00	1.00	2.50	15.00	12.20	5.00	13.83	23.34	5.60
80.01	2.00	1.00	2.50	15.00	19.10	25.00	16.68	-35.39	-10.60
80.01	2.00	1.00	2.50	15.00	25.45	35.00	19.41	-90.50	-29.09
80.01	2.00	1.00	2.50	15.00	35.25	45.00	24.05	-178.17	-60.65
80.01	2.00	1.00	2.50	25.00	18.39	5.00	22.52	56.23	15.10
80.01	2.00	1.00	2.50	25.00	21.04	15.00	23.48	33.61	9.78
80.01	2.00	1.00	2.50	25.00	30.96	35.00	27.41	-52.37	-17.52

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
80.0	2.00	1.00	2.50	25.00	39.98	45.00	31.66	-133.57	-46.79
80.0	2.00	1.00	2.50	35.00	23.19	5.00	30.67	101.33	29.41
80.0	2.00	1.00	2.50	35.00	25.72	15.00	31.52	80.09	24.62
80.0	2.00	1.00	2.50	35.00	29.43	25.00	32.82	48.24	15.62
80.0	2.00	1.00	2.50	35.00	43.10	45.00	38.85	-73.05	-26.29
80.0	2.00	1.00	2.50	45.00	26.52	5.00	37.96	159.84	49.13
80.0	2.00	1.00	2.50	45.00	28.91	15.00	38.69	139.88	44.90
80.0	2.00	1.00	2.50	45.00	32.39	25.00	39.81	110.33	36.01
80.0	2.00	1.00	2.50	45.00	37.54	35.00	41.68	65.71	22.67
100.0	2.00	1.00	2.50	5.00	7.51	15.00	6.26	-21.03	-4.83
100.0	2.00	1.00	2.50	5.00	11.10	25.00	8.02	-51.87	-13.59
100.0	2.00	1.00	2.50	5.00	16.56	35.00	10.70	-99.06	-28.93
100.0	2.00	1.00	2.50	5.00	25.01	45.00	14.86	-173.49	-55.19
100.0	2.00	1.00	2.50	15.00	12.33	5.00	13.90	20.57	4.56
100.0	2.00	1.00	2.50	15.00	18.51	25.00	16.52	-30.19	-8.49
100.0	2.00	1.00	2.50	15.00	23.84	35.00	18.89	-76.03	-23.23
100.0	2.00	1.00	2.50	15.00	31.93	45.00	22.61	-140.16	-48.38
100.0	2.00	1.00	2.50	25.00	19.22	5.00	22.73	49.01	12.20
100.0	2.00	1.00	2.50	25.00	21.50	15.00	23.64	29.41	7.92
100.0	2.00	1.00	2.50	25.00	30.05	35.00	27.04	-44.27	-14.18
100.0	2.00	1.00	2.50	25.00	37.69	45.00	30.43	-112.66	-38.04
100.0	2.00	1.00	2.50	35.00	24.71	5.00	31.18	80.22	24.09
100.0	2.00	1.00	2.50	35.00	26.98	15.00	31.90	69.13	20.21
100.0	2.00	1.00	2.50	35.00	30.20	25.00	33.13	41.40	12.85
100.0	2.00	1.00	2.50	35.00	42.11	45.00	38.11	-63.15	-22.01
100.0	2.00	1.00	2.50	45.00	28.81	5.00	38.95	140.26	41.12
100.0	2.00	1.00	2.50	45.00	30.95	15.00	39.63	122.24	37.68
100.0	2.00	1.00	2.50	45.00	34.00	25.00	40.67	96.42	31.09
100.0	2.00	1.00	2.50	45.00	38.46	35.00	42.25	57.56	19.30
120.0	2.00	1.00	2.50	5.00	7.28	15.00	6.23	-19.01	-4.02
120.0	2.00	1.00	2.50	5.00	10.45	25.00	7.88	-46.15	-11.30
120.0	2.00	1.00	2.50	5.00	15.16	35.00	10.30	-86.74	-24.02
120.0	2.00	1.00	2.50	5.00	22.32	45.00	13.96	-149.43	-45.58
120.0	2.00	1.00	2.50	15.00	12.75	5.00	13.93	10.67	3.80
120.0	2.00	1.00	2.50	15.00	18.11	25.00	16.42	-26.69	-7.08
120.0	2.00	1.00	2.50	15.00	22.74	35.00	18.57	-66.31	-19.31
120.0	2.00	1.00	2.50	15.00	29.66	45.00	21.79	-127.61	-40.13
120.0	2.00	1.00	2.50	25.00	19.79	5.00	22.86	44.10	10.22
120.0	2.00	1.00	2.50	25.00	21.94	15.00	23.73	25.79	6.63
120.0	2.00	1.00	2.50	25.00	29.41	35.00	26.82	-38.62	-11.08
120.0	2.00	1.00	[illegible]	25.00	36.07	45.00	29.78	-97.24	-31.76
120.0	2.00	1.00	[illegible]	35.00	25.79	5.00	31.50	78.96	20.36
120.0	2.00	1.00	2.50	35.00	27.87	15.00	32.27	61.42	17.18
120.0	2.00	1.00	2.50	35.00	30.77	25.00	33.35	36.58	10.99
120.0	2.00	1.00	2.50	35.00	41.25	45.00	37.65	-55.32	-18.73
120.0	2.00	1.00	2.50	45.00	30.48	5.00	39.59	125.72	35.22
120.0	2.00	1.00	2.50	45.00	32.46	15.00	40.25	109.03	32.33
120.0	2.00	1.00	2.50	45.00	35.21	25.00	41.19	85.56	26.70
120.0	2.00	1.00	2.50	45.00	39.19	35.00	42.66	51.35	16.76
80.0	2.00	1.00	4.00	5.00	8.11	15.00	5.43	-26.11	-6.49

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass t/s g/s
100.0	4.00	1.00	4.00	5.00	8.40	25.00	5.68	-56.80	-14.62
100.0	4.00	1.00	4.00	5.00	11.42	35.00	6.23	-108.91	-31.09
100.0	4.00	1.00	4.00	5.00	16.21	45.00	7.17	-192.22	-59.53
100.0	4.00	1.00	4.00	15.00	13.61	5.00	14.74	22.84	5.13
100.0	4.00	1.00	4.00	15.00	16.96	25.00	15.31	-33.69	-9.36
100.0	4.00	1.00	4.00	15.00	19.99	35.00	15.84	-85.43	-25.69
100.0	4.00	1.00	4.00	15.00	24.72	45.00	16.68	-168.23	-53.91
100.0	4.00	1.00	4.00	25.00	21.70	5.00	24.50	56.06	14.25
100.0	4.00	1.00	4.00	25.00	23.03	15.00	24.67	33.21	9.15
100.0	4.00	1.00	4.00	25.00	27.94	35.00	25.45	-51.35	-16.21
100.0	4.00	1.00	4.00	25.00	32.60	45.00	26.27	-133.05	-44.09
100.0	4.00	1.00	4.00	35.00	28.88	5.00	34.05	165.30	29.57
100.0	4.00	1.00	4.00	35.00	30.19	15.00	34.24	82.90	24.64
100.0	4.00	1.00	4.00	35.00	32.09	25.00	34.51	50.08	15.66
100.0	4.00	1.00	4.00	35.00	39.52	45.00	35.80	-79.89	-27.30
100.0	4.00	1.00	4.00	45.00	34.76	5.00	43.24	178.53	54.14
100.0	4.00	1.00	4.00	45.00	36.04	15.00	43.43	156.79	49.46
100.0	4.00	1.00	4.00	45.00	37.88	25.00	43.71	125.04	40.88
100.0	4.00	1.00	4.00	45.00	40.66	35.00	44.16	76.33	25.76
120.0	4.00	1.00	4.00	5.00	6.26	15.00	5.28	-20.77	-4.33
120.0	4.00	1.00	4.00	5.00	8.03	25.00	5.65	-50.41	-12.11
120.0	4.00	1.00	4.00	5.00	10.62	35.00	6.16	-94.96	-25.64
120.0	4.00	1.00	4.00	5.00	14.62	45.00	6.97	-164.46	-40.74
120.0	4.00	1.00	4.00	15.00	13.74	5.00	14.75	20.67	4.27
120.0	4.00	1.00	4.00	15.00	16.73	25.00	15.30	-29.57	-7.74
120.0	4.00	1.00	4.00	15.00	19.27	35.00	15.71	-74.03	-21.21
120.0	4.00	1.00	4.00	15.00	23.30	45.00	16.50	-143.01	-44.11
120.0	4.00	1.00	4.00	25.00	22.04	5.00	24.51	49.02	11.88
120.0	4.00	1.00	4.00	25.00	23.26	15.00	24.70	29.23	7.59
120.0	4.00	1.00	4.00	25.00	27.50	35.00	25.36	-44.20	-13.39
120.0	4.00	1.00	4.00	25.00	31.46	45.00	26.09	-112.49	-36.06
120.0	4.00	1.00	4.00	35.00	29.62	5.00	34.17	92.55	24.57
120.0	4.00	1.00	4.00	35.00	30.80	15.00	34.33	72.13	20.43
120.0	4.00	1.00	4.00	35.00	32.49	25.00	34.58	43.20	12.97
120.0	4.00	1.00	4.00	35.00	36.79	45.00	35.60	-67.65	-22.47
120.0	4.00	1.00	4.00	45.00	36.09	5.00	43.55	155.71	45.19
120.0	4.00	1.00	4.00	45.00	37.25	15.00	43.71	135.79	41.24
120.0	4.00	1.00	4.00	45.00	38.88	25.00	43.95	107.47	34.02
120.0	4.00	1.00	4.00	45.00	41.29	35.00	44.32	65.10	21.30

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
100.00	4.00	1.00	2.50	25.00	31.91	45.00	28.73	-121.45	-40.70
100.00	4.00	1.00	2.50	35.00	29.45	5.00	32.44	95.42	26.39
100.00	4.00	1.00	2.50	35.00	30.65	15.00	32.99	75.10	22.12
100.00	4.00	1.00	2.50	35.00	32.37	25.00	33.76	45.20	14.10
100.00	4.00	1.00	2.50	35.00	39.03	45.00	36.91	-72.07	-24.92
100.00	4.00	1.00	2.50	45.00	35.88	5.00	41.18	157.14	47.51
100.00	4.00	1.00	2.50	45.00	37.02	15.00	41.63	139.64	43.59
100.00	4.00	1.00	2.50	45.00	38.67	25.00	42.30	111.23	36.14
100.00	4.00	1.00	2.50	45.00	41.16	35.00	43.33	68.00	22.88
120.00	4.00	1.00	2.50	5.00	6.17	15.00	6.03	-19.30	-4.09
120.00	4.00	1.00	2.50	5.00	7.81	25.00	7.43	-47.02	-11.47
120.00	4.00	1.00	2.50	5.00	10.21	35.00	9.43	-80.52	-24.38
120.00	4.00	1.00	2.50	5.00	13.96	45.00	12.44	-153.01	-46.38
120.00	4.00	1.00	2.50	15.00	13.84	5.00	14.15	19.20	3.93
120.00	4.00	1.00	2.50	15.00	16.61	25.00	16.14	-27.42	-7.25
120.00	4.00	1.00	2.50	15.00	18.97	35.00	[illegible].76	-68.57	-19.88
120.00	4.00	1.00	2.50	15.00	22.67	45.00	[illegible].28	-132.33	-41.38
120.00	4.00	1.00	2.50	25.00	22.29	5.00	[illegible]	45.94	10.73
120.00	4.00	1.00	2.50	25.00	23.39	15.00	24.04	26.88	6.93
120.00	4.00	1.00	2.50	25.00	27.32	35.00	26.34	-40.49	-12.40
120.00	4.00	1.00	2.50	25.00	35.90	45.00	28.41	-103.17	-33.45
120.00	4.00	1.00	2.50	35.00	30.10	5.00	32.50	84.25	21.98
120.00	4.00	1.00	2.50	35.00	31.19	15.00	33.12	65.73	18.43
120.00	4.00	1.00	2.50	35.00	32.71	25.00	33.86	39.26	11.74
120.00	4.00	1.00	2.50	35.00	38.47	45.00	36.76	-64.80	-20.44
120.00	4.00	1.00	2.50	45.00	37.00	5.00	41.50	139.51	39.78
120.00	4.00	1.00	2.50	45.00	38.05	15.00	41.93	121.51	36.46
120.00	4.00	1.00	2.50	45.00	39.52	25.00	42.56	96.08	30.20
120.00	4.00	1.00	2.50	45.00	41.68	35.00	43.49	58.09	19.02
80.00	4.00	1.00	4.00	5.00	6.59	15.00	5.30	-26.41	-6.55
80.00	4.00	1.00	4.00	5.00	8.97	25.00	5.72	-66.53	-18.44
80.00	4.00	1.00	4.00	5.00	12.66	35.00	6.36	-130.37	-39.48
80.00	4.00	1.00	4.00	5.00	18.60	45.00	7.50	-235.72	-76.45
80.00	4.00	1.00	4.00	15.00	13.41	5.00	14.72	26.10	6.44
80.00	4.00	1.00	4.00	15.00	17.32	25.00	15.34	-39.96	-11.82
80.00	4.00	1.00	4.00	15.00	21.01	35.00	15.96	-103.20	-32.64
80.00	4.00	1.00	4.00	15.00	26.91	45.00	16.98	-207.72	-69.20
80.00	4.00	1.00	4.00	25.00	21.16	5.00	24.42	65.27	17.87
80.00	4.00	1.00	4.00	25.00	22.69	15.00	24.65	39.31	11.54
80.00	4.00	1.00	4.00	25.00	28.57	35.00	25.54	-62.53	-20.60
80.00	4.00	1.00	4.00	25.00	34.38	45.00	26.60	-164.93	-56.57
80.00	4.00	1.00	4.00	35.00	27.80	5.00	33.90	124.69	37.17
80.00	4.00	1.00	4.00	35.00	29.27	15.00	34.06	98.99	30.95
80.00	4.00	1.00	4.00	35.00	31.50	25.00	34.40	60.46	19.72
80.00	4.00	1.00	4.00	35.00	40.58	45.00	36.09	-98.86	-34.81
80.00	4.00	1.00	4.00	45.00	32.85	5.00	42.76	212.16	67.35
80.00	4.00	1.00	4.00	45.00	34.28	15.00	42.96	187.56	61.54
80.00	4.00	1.00	4.00	45.00	36.43	25.00	43.30	150.73	50.95
80.00	4.00	1.00	4.00	45.00	39.74	35.00	43.86	92.73	32.17
100.00	4.00	1.00	4.00	5.00	6.40	15.00	5.29	-23.02	-5.22

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
120.0	4.00	1.00	1.00	5.00	6.92	25.00	14.06	-32.62	-8.43
120.0	4.00	1.00	1.00	5.00	8.57	35.00	20.26	-61.33	-18.00
120.0	5.00	1.00	1.00	5.00	11.22	45.00	27.84	-105.53	-33.93
120.0	4.00	1.00	1.00	15.00	14.20	5.00	11.60	13.26	2.61
120.0	4.00	1.00	1.00	15.00	16.11	25.00	19.23	-10.98	-5.11
120.0	4.00	1.00	1.00	15.00	17.73	35.00	24.56	-47.12	-14.15
120.0	4.00	1.00	1.00	15.00	20.26	45.00	31.23	-98.52	-29.44
120.0	4.00	1.00	1.00	25.00	23.12	5.00	18.78	31.43	6.89
120.0	4.00	1.00	1.00	25.00	23.89	15.00	21.52	18.43	4.63
120.0	4.00	1.00	1.00	25.00	26.60	35.00	29.48	-27.51	-8.61
120.0	4.00	1.00	1.00	25.00	29.04	45.00	35.23	-69.75	-23.14
120.0	4.00	1.50	1.00	35.00	31.65	5.00	26.46	57.11	13.87
120.0	4.00	1.00	1.00	35.00	32.40	15.00	28.59	44.48	11.98
120.0	4.00	1.00	1.00	35.00	33.45	25.00	31.34	26.58	7.82
120.0	4.00	1.00	1.00	35.00	37.34	45.00	39.04	-40.77	-14.05
120.0	4.00	1.00	1.00	45.00	39.61	5.00	34.36	93.61	24.98
120.0	4.00	1.00	1.00	45.00	40.34	15.00	36.00	81.57	23.42
120.0	4.00	1.00	1.00	45.00	41.33	25.00	38.13	64.36	19.74
120[illegible]	[illegible]	1.00	1.00	45.00	42.78	35.00	41.03	38.85	12.60
[illegible]	[illegible]	1.00	2.50	5.00	6.48	15.00	6.09	-24.60	-6.16
[illegible]	[illegible]	1.00	2.50	5.00	8.67	25.00	7.66	-61.94	-17.39
[illegible]	[illegible]	1.00	2.50	5.00	12.08	35.00	10.63	-121.20	-37.29
80.0	4.00	1.00	2.50	5.00	17.68	45.00	13.70	-218.39	-72.10
80.0	4.00	1.00	2.50	13.00	13.53	5.00	14.11	24.21	5.91
80.0	4.00	1.00	2.50	15.00	17.15	25.00	16.26	-36.86	-11.00
80.0	4.00	1.00	2.50	15.00	20.49	35.00	18.18	-95.26	-30.41
80.0	4.00	1.00	2.50	15.00	25.94	45.00	21.33	-190.64	-64.26
80.0	4.00	1.00	2.50	25.00	21.48	5.00	23.26	59.66	16.15
80.0	4.00	1.00	2.50	25.00	22.88	15.00	23.95	35.87	10.47
80.0	4.00	1.00	2.50	25.00	2[illegible].27	35.00	26.62	-56.75	-18.08
80.0	4.00	1.00	2.50	25.00	33.50	45.00	29.29	-149.21	-51.77
80.0	4.00	1.00	2.50	35.00	28.51	5.00	32.23	112.11	32.97
80.0	4.00	1.00	2.50	35.00	29.85	15.00	32.78	89.04	27.61
80.0	4.99	1.00	2.50	35.00	31.86	25.00	33.63	54.38	17.68
80.0	4.00	1.00	2.50	35.00	39.98	45.00	37.32	-87.85	-31.30
80.0	4.00	1.00	2.50	45.00	34.24	5.00	40.67	187.82	58.82
80.0	4.00	1.00	2.50	45.00	35.52	15.00	41.14	165.94	53.95
80.0	4.00	1.00	2.50	45.00	37.43	25.00	41.85	133.08	44.75
80.0	4.00	1.00	2.50	45.00	40.36	35.00	43.00	81.65	28.26
100.0	4.00	1.00	2.50	5.00	6.29	15.00	6.06	-21.46	-4.91
100.0	4.00	1.00	2.50	5.00	8.15	25.00	7.53	-52.95	-13.82
100.0	4.00	1.00	2.50	5.00	10.95	35.00	9.67	-101.43	-29.48
100.0	4.00	1.00	2.50	5.00	15.42	45.00	12.98	-178.57	-56.44
100.0	4.00	1.00	2.50	15.00	13.71	5.00	14.14	21.20	4.72
100.0	4.00	1.00	2.50	15.00	16.82	25.00	16.18	-31.18	-8.74
100.0	4.00	1.00	2.50	15.00	19.57	35.00	17.92	-79.14	-24.05
100.0	4.00	1.00	2.50	15.00	23.95	45.00	20.68	-155.22	-50.35
100.0	4.00	1.00	2.50	25.00	21.96	5.00	23.35	51.43	12.90
100.0	4.00	1.00	2.50	25.00	23.19	15.00	24.02	30.52	8.36
100.0	4.00	1.00	2.50	25.00	27.69	35.00	26.44	-46.99	-14.98

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
120.0	2.00	1.00	4.00	25.00	37.31	45.00	27.12	-108.46	-34.97
120.0	2.00	1.00	4.00	35.00	24.72	5.00	33.40	88.40	23.30
120.0	2.00	1.00	4.00	35.00	27.01	15.00	33.69	68.72	19.36
120.0	2.00	1.00	4.00	35.00	30.25	25.00	34.17	40.94	12.26
120.0	2.00	1.00	4.00	35.00	42.02	45.00	36.45	-62.67	-20.96
120.0	2.00	1.00	4.00	45.00	28.57	5.00	41.84	142.05	40.62
120.0	2.00	1.00	4.00	45.00	30.81	15.00	42.16	123.28	37.05
120.0	2.00	1.00	4.00	45.00	33.92	25.00	42.65	96.82	30.44
120.0	2.00	1.00	4.00	45.00	38.42	35.00	43.46	57.85	18.94
80.0	4.00	1.00	1.00	5.00	6.01	15.00	9.16	-17.00	-4.39
80.0	4.00	1.00	1.00	5.00	7.51	25.00	14.44	-42.93	-12.59
80.0	4.00	1.00	1.00	5.00	9.95	35.00	21.12	-83.48	-26.90
80.0	4.00	1.00	1.00	5.00	13.74	45.00	29.24	-149.47	-51.35
80.0	4.00	1.00	1.00	15.00	13.99	5.00	11.61	16.71	3.96
80.0	4.00	1.00	1.00	15.00	16.40	25.00	19.38	-25.29	-7.69
80.0	4.00	1.00	1.00	15.00	18.78	35.00	25.06	-65.5[illegible]	-21.26
80.0	4.00	1.00	1.00	15.00	22.50	45.00	32.29	-129.01	-44.63
80.0	4.00	1.00	1.00	25.00	22.60	5.00	18.84	40.77	10.53
80.0	4.00	1.00	1.00	25.00	23.54	15.00	21.46	24.44	7.00
80.0	4.00	1.00	1.00	25.00	27.21	35.00	29.72	-38.38	-13.03
80.0	4.00	1.00	1.00	25.00	30.68	45.00	35.93	-100.28	-35.53
80.0	4.00	1.00	1.00	35.00	30.64	5.00	26.46	75.88	21.20
80.0	4.00	1.00	1.00	35.00	31.55	15.00	28.45	60.20	18.15
80.0	4.00	1.00	1.00	35.00	32.90	25.00	31.19	36.64	11.78
80.0	4.00	1.00	1.00	35.00	38.33	45.00	40.25	-38.50	-21.31
80.0	4.00	1.00	1.00	45.00	37.79	5.00	34.00	126.07	37.63
80.0	4.00	1.00	1.00	45.00	38.65	15.00	35.58	111.26	35.09
80.0	4.00	1.00	1.00	45.00	39.93	25.00	37.69	89.08	29.47
80.0	4.00	1.00	1.00	45.00	41.90	35.00	40.69	54.55	18.76
100.0	4.00	1.00	1.00	5.00	5.88	15.00	9.10	-14.90	-3.52
100.0	4.00	1.00	1.00	5.00	7.16	25.00	14.22	-36.73	-10.09
100.0	4.00	1.00	1.00	5.00	9.12	35.00	20.63	-70.11	-21.54
100.0	4.00	1.00	1.00	5.00	12.25	45.00	28.46	-122.75	-40.78
100.0	4.00	1.00	1.00	15.00	14.11	5.00	11.61	14.64	3.14
100.0	4.00	1.00	1.00	15.00	16.25	25.00	19.29	-21.45	-6.14
100.0	4.00	1.00	1.00	15.00	18.14	35.00	24.77	-54.23	-16.99
100.0	4.00	1.00	1.00	15.00	21.10	45.00	31.66	-105.80	-35.47
100.0	4.00	1.00	1.00	25.00	22.90	5.00	18.82	35.16	8.34
100.0	4.00	1.00	1.00	25.00	23.76	15.00	21.50	20.84	5.58
100.0	4.00	1.00	1.00	25.00	26.86	35.00	29.59	-31.81	-10.36
100.0	4.00	1.00	1.00	25.00	29.69	45.00	35.52	-81.85	-28.04
100.0	4.00	1.00	1.00	35.00	31.23	5.00	26.47	64.60	16.79
100.0	4.00	1.00	1.00	35.00	32.05	15.00	28.54	50.76	14.45
100.0	4.00	1.00	1.00	35.00	33.23	25.00	31.29	30.63	9.41
100.0	4.00	1.00	1.00	35.00	37.72	45.00	40.00	-47.92	-16.97
100.0	4.00	1.00	1.00	45.00	38.87	5.00	34.28	106.75	30.04
100.0	4.00	1.00	1.00	45.00	39.65	15.00	35.85	93.57	28.13
100.0	4.00	1.00	1.00	45.00	40.76	25.00	37.96	74.32	23.66
100.0	4.00	1.00	1.00	45.00	42.42	35.00	40.90	45.19	15.08
120.0	4.00	1.00	1.00	5.00	5.80	15.00	9.06	-13.45	-2.93

Table P.2 (Cont) Simulated database

Air pressure drop Pa	Water flow rate kg/s	Air mass flow rate (dry) kg/s	hcA W/°C	Inlet water temperature °C	Outlet water temperature °C	Inlet wet-bulb temperature °C	Outlet wet-bulb temperature °C	Duty kW	Mass transfer g/s
80.0	2.00	1.00	4.00	5.00	12.72	25.00	6.04	-65.80	-18.28
80.0	2.00	1.00	4.00	5.00	19.93	35.00	7.14	-128.54	-39.05
80.0	2.00	1.00	4.00	5.00	31.39	45.00	9.36	-221.03	-75.32
80.0	2.00	1.00	4.00	15.00	11.94	5.00	14.57	25.70	6.31
80.0	2.00	1.00	4.00	15.00	19.51	25.00	15.61	-39.07	-11.59
80.0	2.00	1.00	4.00	15.00	26.57	35.00	16.83	-100.20	-31.84
80.0	2.00	1.00	4.00	15.00	37.50	45.00	19.29	-199.07	-66.90
80.0	2.00	1.00	4.00	25.00	17.63	5.00	23.80	62.59	17.09
80.0	2.00	1.00	4.00	25.00	20.59	15.00	24.29	37.53	10.98
80.0	2.00	1.00	4.00	25.00	31.69	35.00	26.25	-58.78	-19.47
80.0	2.00	1.00	4.00	25.00	41.82	45.00	29.26	-149.76	-51.91
80.0	2.00	1.00	4.00	35.00	21.68	5.00	32.51	114.19	33.66
80.0	2.00	1.00	4.00	35.00	24.52	15.00	32.94	90.23	28.91
80.0	2.00	1.00	4.00	35.00	28.71	25.00	33.63	54.42	17.69
80.0	2.00	1.00	4.00	35.00	44.07	45.00	38.04	-80.99	-28.91
80.0	2.00	1.00	4.00	45.00	24.08	5.00	40.00	180.50	56.28
80.0	2.00	1.00	4.00	45.00	26.80	15.00	40.40	157.70	51.00
80.0	2.00	1.00	4.00	45.00	30.79	25.00	41.07	124.06	41.59
80.0	2.00	1.00	4.00	45.00	36.68	35.00	42.31	73.22	25.30
100.0	2.00	1.00	4.00	5.00	7.73	15.00	5.40	-22.79	-5.17
100.0	2.00	1.00	4.00	5.00	11.64	25.00	5.94	-56.27	-14.52
100.0	2.00	1.00	4.00	5.00	17.57	35.00	6.80	-107.74	-30.85
100.0	2.00	1.00	4.00	5.00	26.83	45.00	8.39	-189.50	-58.96
100.0	2.00	1.00	4.00	15.00	12.30	5.00	14.61	22.51	5.04
100.0	2.00	1.00	4.30	15.00	18.84	25.00	15.51	-33.14	-9.23
100.0	2.00	1.00	4.00	15.00	24.71	35.00	16.44	-83.60	-25.26
100.0	2.00	1.00	4.00	15.00	33.67	45.00	18.04	-164.04	-52.84
100.0	2.00	1.00	4.00	25.00	18.61	5.00	24.09	54.39	13.76
100.0	2.00	1.00	4.00	25.00	21.21	15.00	24.42	32.14	8.83
100.0	2.00	1.00	4.00	25.00	30.63	35.00	25.91	-49.33	-15.64
100.0	2.00	1.00	4.00	25.00	39.23	45.00	27.74	-126.26	-42.13
100.0	2.00	1.00	4.00	35.00	23.45	5.00	33.06	99.12	27.57
100.0	2.00	1.00	4.00	35.00	25.98	15.00	33.41	77.69	22.95
100.0	2.00	1.00	4.00	35.00	29.61	25.00	33.98	46.67	14.55
100.0	2.00	1.00	4.00	35.00	43.01	45.00	37.04	-71.09	-24.52
100.0	2.00	1.00	4.00	45.00	26.65	5.00	41.14	158.74	47.37
100.0	2.00	1.00	4.00	45.00	29.08	15.00	41.48	138.27	43.12
100.0	2.00	1.00	4.00	45.00	32.54	25.00	42.04	108.04	35.32
100.0	2.00	1.00	4.00	45.00	37.62	35.00	43.02	64.89	21.82
120.0	2.00	1.00	4.00	5.00	7.48	15.00	5.39	-20.58	-4.30
120.0	2.00	1.00	4.00	5.00	10.93	25.00	5.88	-49.98	-12.03
120.0	2.00	1.00	4.00	5.00	15.99	35.00	6.50	-94.17	-25.50
120.0	2.00	1.00	4.00	5.00	23.84	45.00	7.98	-162.66	-48.39
120.0	2.00	1.00	4.00	15.00	12.56	5.00	14.65	20.41	4.20
120.0	2.00	1.00	4.00	15.00	18.39	25.00	15.45	-27.19	-7.66
120.0	2.00	1.00	4.00	15.00	23.43	35.00	16.20	-72.78	-20.92
120.0	2.00	1.00	4.00	15.00	31.10	45.00	17.50	-140.34	-43.47
120.0	2.00	1.00	4.00	25.00	19.27	5.00	24.21	48.75	11.50
120.0	2.00	1.00	4.00	25.00	21.64	15.00	24.58	28.51	7.39
120.0	2.00	1.00	4.00	25.00	29.90	35.00	25.74	-42.77	-13.01

Table P.2 (Cont) Simulated database

APPENDIX Q Determination of the relationship $L = f(Z, N^*)$

The appropriate value of c^*_{aw} must lie between its value at the water inlet temperature and that at the air inlet wet-bulb temperature. This may be described by:

$$c^*_{aw} = L\, c^*_{awi} + (1 - L)\, c^*_{aai} \qquad (Q.1)$$

where

L = 0 to 1

The term L will have a value between 0 and 1 depending on the ratio of thermal capacities and the value of the design characteristic, thus:

$$L = f\,(\dot{m}_w/\dot{m}_a\ ,\ N^*) \qquad (Q.2)$$

Based on the selected universal values of:

$[(\alpha/\beta)\ c_{avaf}{}^*]$ = 1,00 for all applications

$(\alpha/\gamma)\,i$ = 1,00 for water cooling
= 1,05 for air cooling,

a set of values of c^*_{aw} was calculated for each test and values of L for each test was then determined. Note, this included the large database of simulated tests which were calculated in order to supplement the experimental database.

Based on this information a curve fitting exercise was undertaken, with the following result:

$$L = (\dot{m}_w/\dot{m}_a)^{1,3}/[0,5N^{-0,5} + (\dot{m}_w/\dot{m}_a)^{1,3}] \qquad (Q.3)$$

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