Using The PEPSE® JW Method to Evaluate The Design Performance of A Feedwater Heater With A Short Drain Cooler

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INTRODUCTION

Electric utilities purchase feedwater heaters for new plants, where they purchase several at a time, and older plants, where the individual heaters are replaced as tube pluggage becomes excessive. A high-pressure feedwater heater costs between one and five hundred thousand dollars depending on its size and design. High-pressure feedwater heaters are essential to the performance of a unit. If a unit is designed to have feedwater heaters in service and they are removed, the furnace heat input must increase. This will increase unit heat rate and may cause furnace tube overheating due to excessive furnace exit gas temperature.

Since feedwater heaters are so important to unit performance, utilities need a method to evaluate the heater manufacturer's performance specifications and understand the theory behind a heater's design. Previously utilities have not had an available method that uses the heater manufacturer's design data and accurately calculates the zone heat transfer coefficients and pressure drop when given only the heater design data. There are computer programs that the heater manufacturers use to design the heater, but these programs are proprietary and would be costly for a utility to use for the small number of heaters analyzed on a yearly basis.

This paper describes the Modified Delaware Method for evaluating the design performance of a feedwater heater and applies it to an actual design using the new "JW Method" in PEPSE.

SHELL-SIDE HEAT TRANSFER ANALYSIS

A short drain cooler feedwater heater, shown in Figure 1, has three zones: a desuperheating, a condensing, and a drain cooling zone. Each zone is treated as a separate heat exchanger in evaluating the heat transfer coefficient and pressure drop. The heater shown in Figure 1 has a short drain cooler that has all the feedwater tubes passing through it and does not span the entire length of the heater. This is in contrast to a long drain cooler (not shown) that does not have all the feedwater tubes passing through it and spans the entire length of the heater. This paper analyzes a heater with a short drain cooler. The method described in this paper may be used for calculating the heat transfer coefficients and shell-side pressure drops for high-pressure heaters. Currently the method gives accurate heat transfer coefficients for low-pressure heaters but overpredicts the pressure drops.

Desuperheating Zone

The turbine extraction steam enters the heater at the desuperheating zone where it is cooled to within 5-35°C(10-60°F) of its saturation point. The first design parameter, the crossflow area, is calculated using the following formula:

$$S_m = \frac{(CM)(A)(S)}{0.866 D_{otl}} = (Cr)S \qquad (1)$$

where S_m represents the crossflow area calculated at the center of the desuperheating zone, Cr represents the crossflow distance, and CM represents a cross flow area multiplier that reflects the actual zone cross flow (see Figure 2). The term A is the semicircular zone cross-sectional area calculated using:

$$A = \pi \frac{D_{otl}^2}{8} \qquad (2)$$

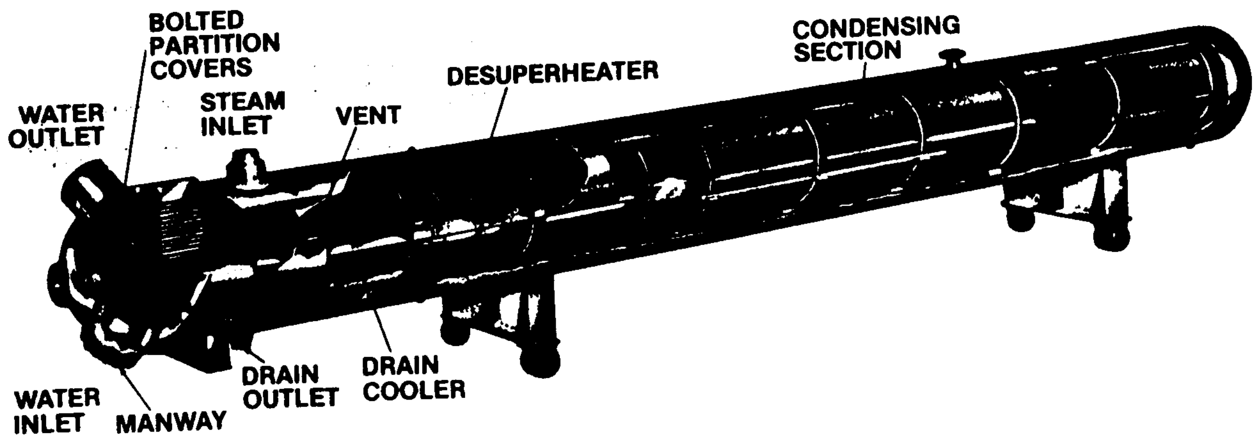

Figure 1: Three Zone Feedwater Heater With Short Drain Cooler With a Desuperheating, Condensing, and Drain Cooling Zone.

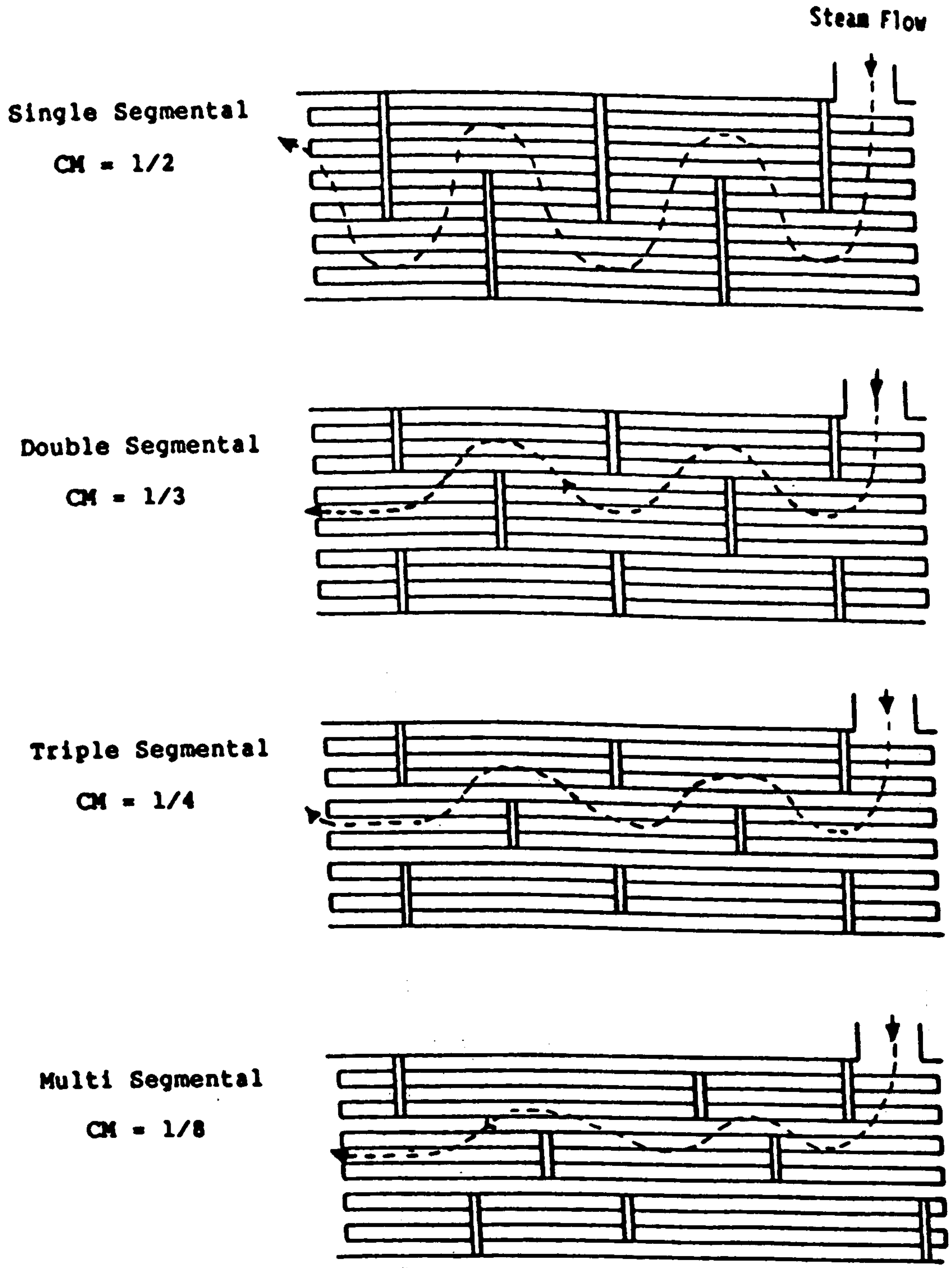

Figure 2: Baffle Types and Cross Flow Multipliers for the Desuperheating and Drain Cooling Zones

This allows the calculation of a Reynolds number, which is proportional to the crossflow area given by Eq. (1) and the steam mass flow rate (Bell, 1986). The Reynolds number is defined by:

$$Re_s = \frac{D_o m_s}{\mu_s S_m} \tag{3}$$

where Re_s is proportional to a friction factor J_f, which is obtained using Figure 3.

The base heat transfer coefficient is calculated by utilizing the Colburn J Factor for heat transfer. The J Factor is given by (Bell, 1986, Incropera and Dewitt, 1981):

$$J_f = St(Pr)^{0.667} = \frac{h}{\rho v C_s}\left(\frac{C_s \mu_s g_c}{k_s}\right)^{0.667}$$

where St and Pr are the Stanton and Prandtl numbers respectively. Solving for the heat transfer coefficient and incorporating the crossflow area calculated in Eq. (1), we obtain (Bell, 1986):

$$h_{base} = \frac{J_f\, C_s\, m_s}{S_m}\left(\frac{k_s}{C_s\, \mu_s\, g_c}\right)^{0.667} \tag{4}$$

The base heat transfer coefficient is calculated assuming that the entire shell-side stream flows across the ideal tube bank formed by the tube array at the centerline of the zone (Bell, 1986). This is the greatest amount of heat transfer attainable. The value obtained is then multiplied by a series of correction factors : J_c,J_l,J_b, and J_s to adjust it for design conditions (Bell, 1986). These are defined next.

J_c: The crossflow correction factor. This factor is obtained using Figures 4 and 6 where it is plotted vs. S_m (Weber, 1992).

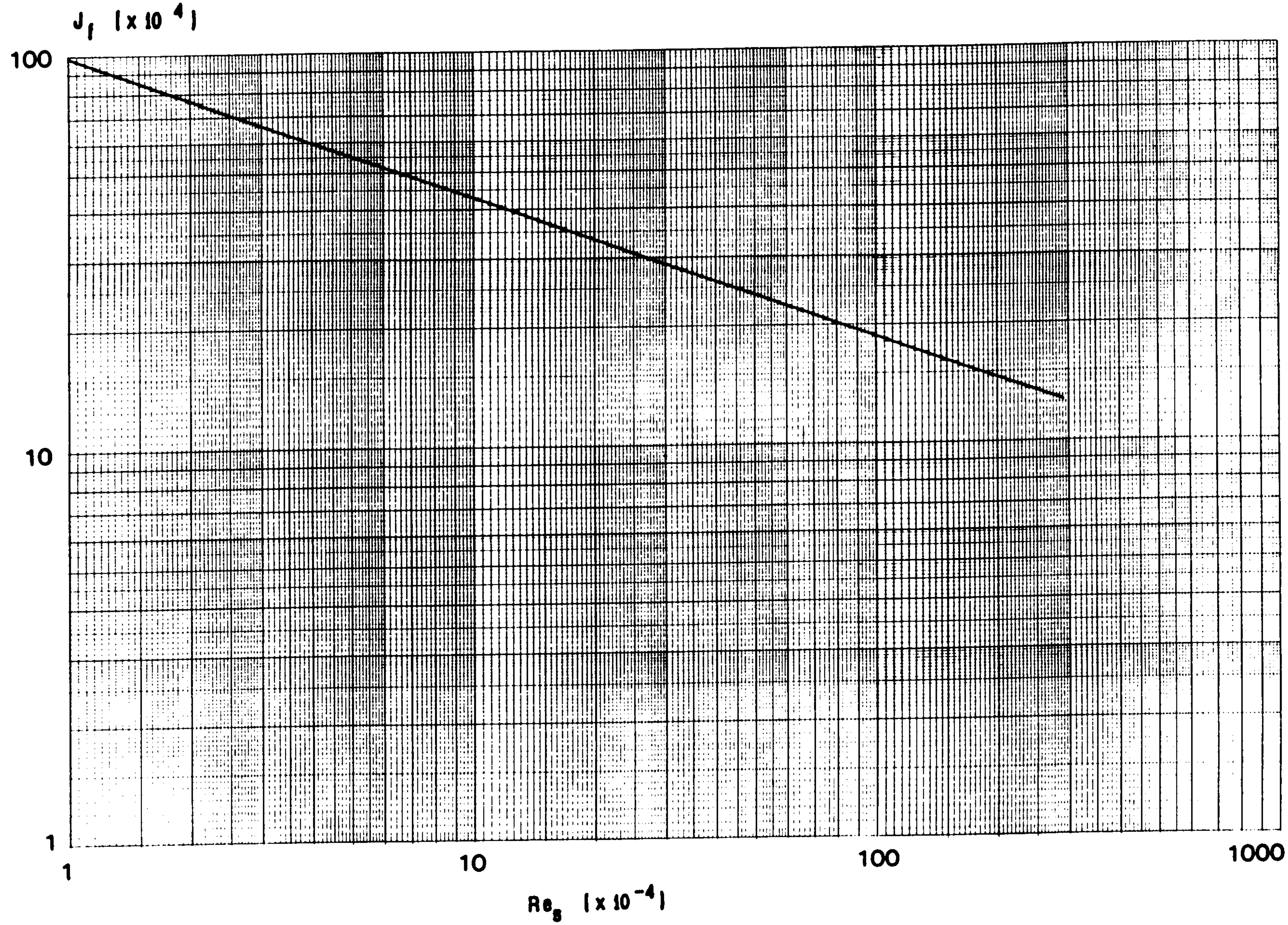

Figure 3: Correlation of J Factor For Ideal Tube Banks

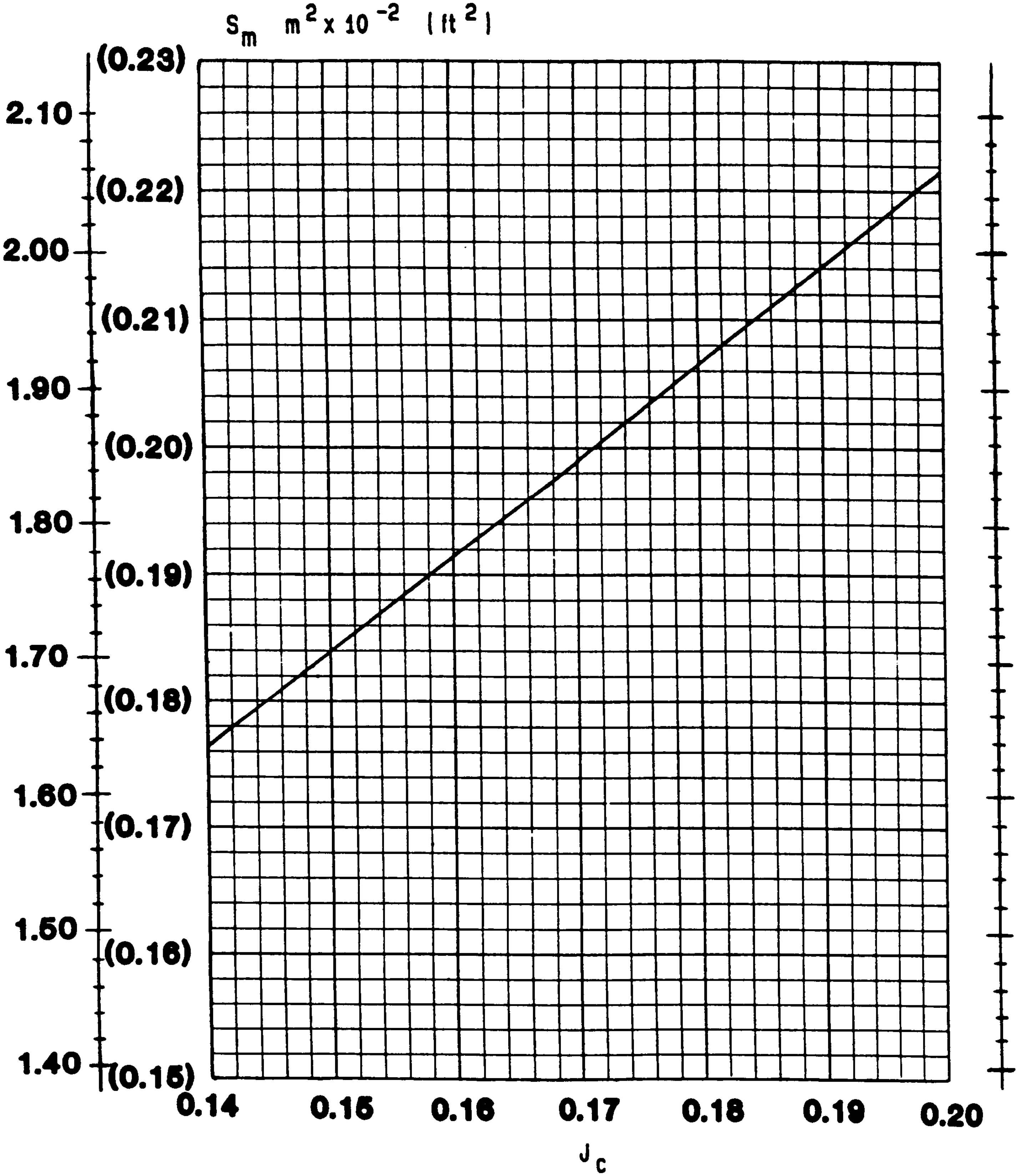

Figure 4: Cross Flow Correction Factor For the Desuperheating Zone

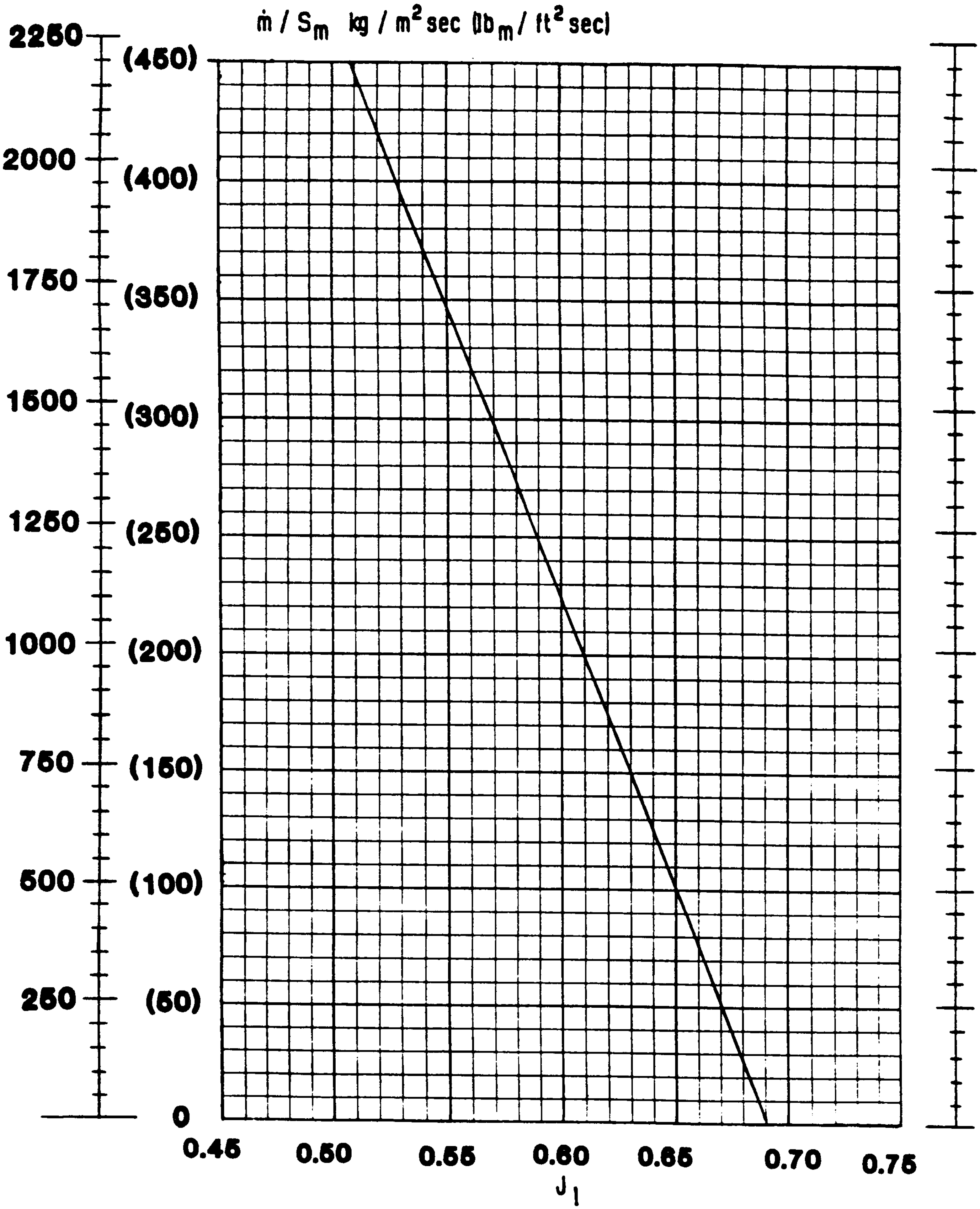

Figure 5: Leakage Correction Factor For the Desuperheating and Drain Cooling Zones

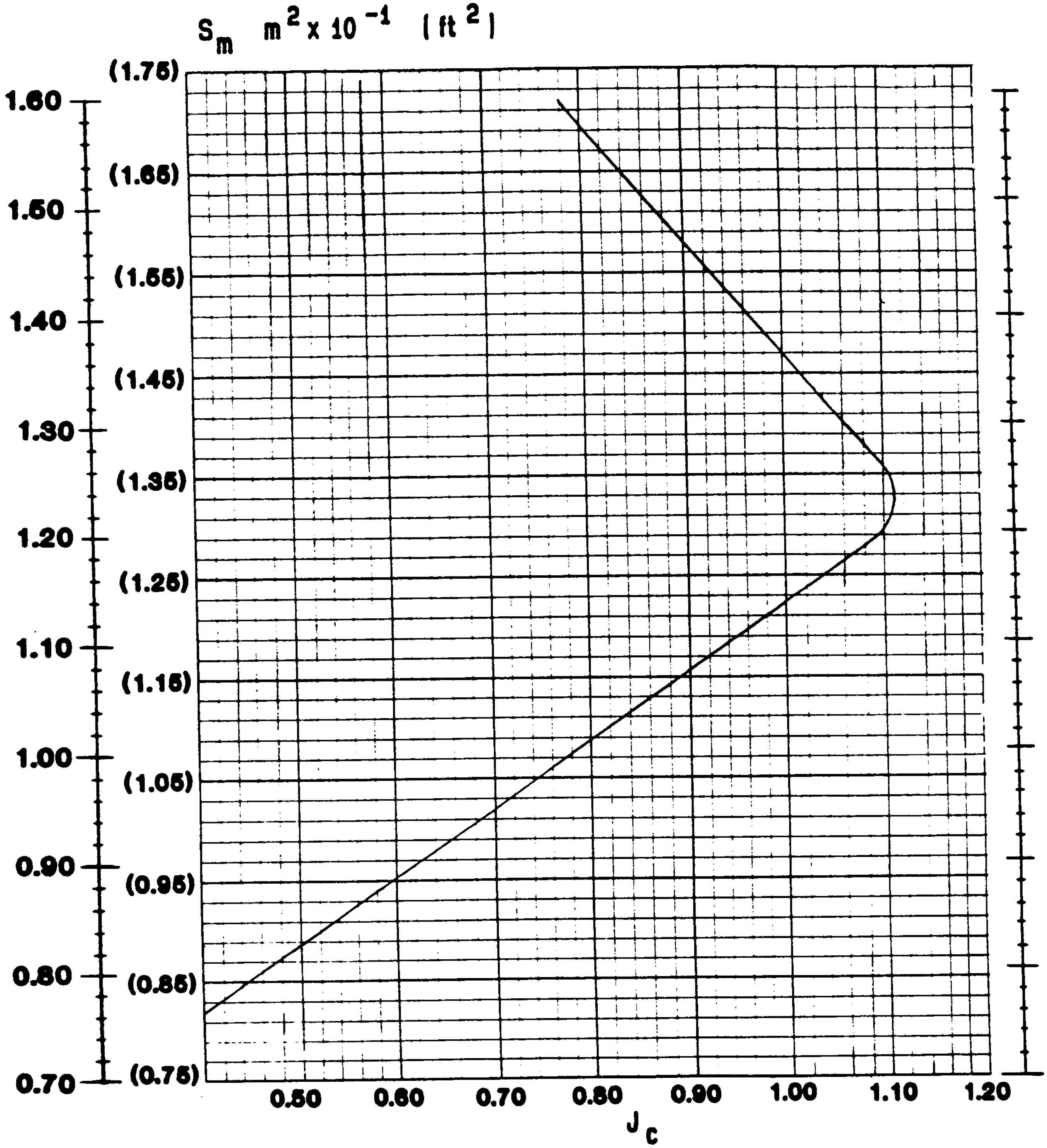

Figure 6: Cross Flow Correction Factor For the Drain Cooling Zone

J_l: The leakage correction factor. This factor includes both shell-to-baffle and tube-to-baffle leakage. It is obtained using Figure 5 where it is plotted verses. the ratio of m_s to S_m (Weber, 1992).

J_b: The zone bypass correction factor. This factor is defined as the steam that passes through the zone but does not come in contact with any tubes or baffles. Design data to calculate this factor is very difficult or impossible to obtain from the heater manufacturer. Therefore this factor is assumed as 0.9,which is representative of a well-designed heater.

J_s: The inlet and outlet baffle spacing correction factor. This factor is obtained using Figure 7 where it is plotted verses N_b and l_s (Bell,1986).

The corrected shell-side zone heat transfer coefficient is determined using:

$$h_o = h_{base} J_c J_l J_b J_s \tag{5}$$

Condensing Zone

The condensing zone shell-side heat transfer coefficient is the easiest to obtain. The method used is explained in detail by Clemmer and Lemezis (1965).

If $T_{sat} > 160°C$ (320°F):

$R_c = 0.0704592\ m^2\ C/kW$ $(0.0004\ hrft^2\ F/Btu)$

If $Tsat < 160°C$ (320°F):

$R_c = 12.03769\ (1.8\ T_{sat} + 32)^{-0.8912}\ m^2\ C/kW$ $(0.06834\ (T_{sat})^{-0.8912}\ hrft^2\ F/Btu$ (6)

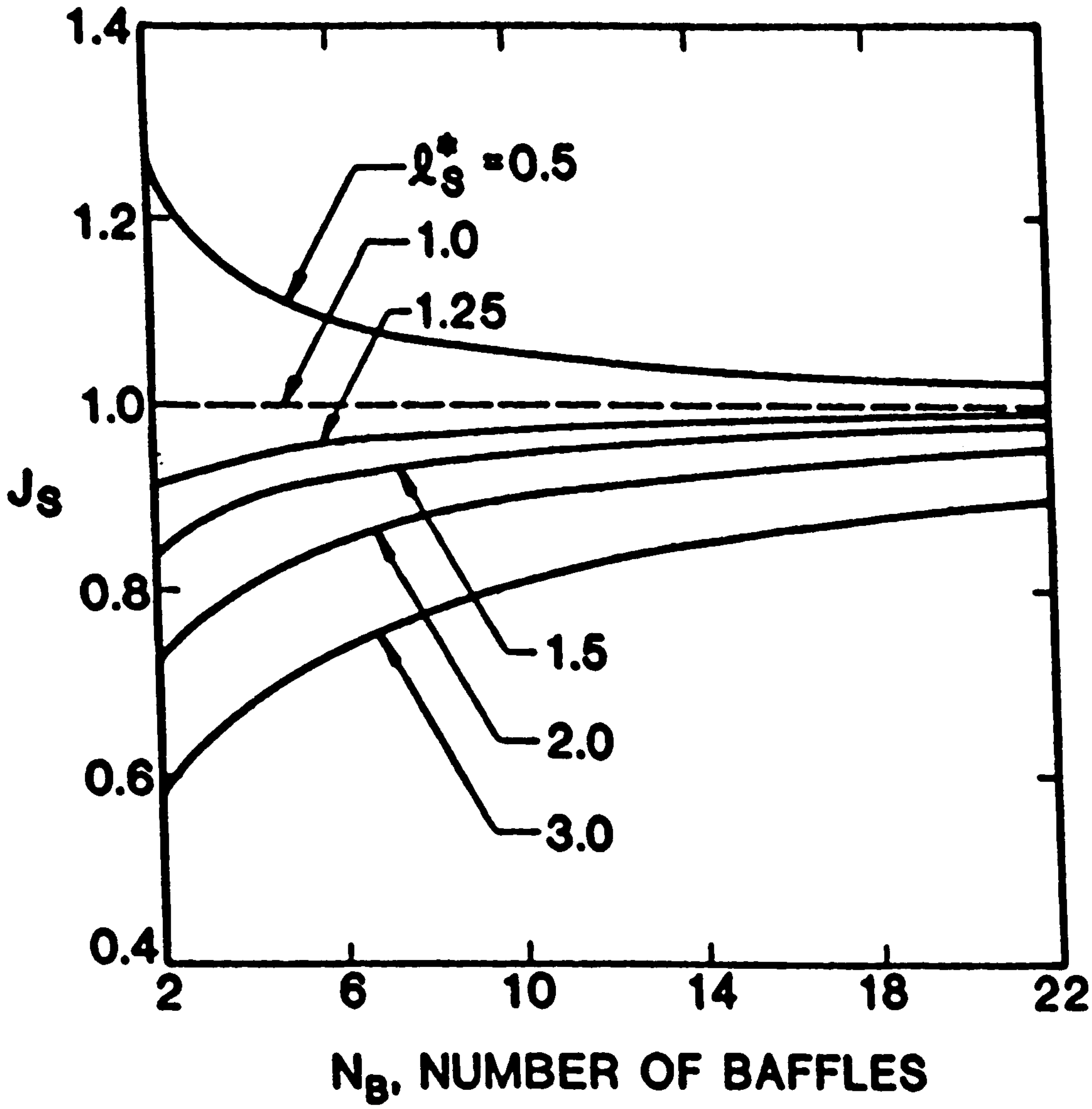

Figure 7: Baffle Spacing Correction Factor For the Desuperheating and Drain Cooling Zones

Note that the quantities on the right in parentheses apply for English units, and the others apply for SI units.

Drain Cooling Zone

The drain cooling zone heat transfer coefficient is calculated in a manner similar to the way it is calculated in the desuperheating zone. Figure 6 illustrates the correction factor J_c as a function of S_m. The leakage correction factor is calculated using Figure 5 as in the desuperheating zone.

TUBE SIDE HEAT TRANSFER ANALYSIS

The tube-side heat transfer coefficient is calculated using the Dittus-Boelter relation given in Eq.12 (Clemmer and Lemezis, 1965). The information necessary to complete this portion of the analysis is the feedwater properties k_f, μ_f,ρ_f,C_f, and V_f:

$$h_i = \left(\frac{k_f}{D_i}\right)(0.023)\,Re^{0.8}\,Pr^{0.4} \qquad (7)$$

where

$$Pr = \frac{C_f\,\mu_f}{k_f} \text{ and } Re = \frac{\rho_f\,V_f D_i}{\mu_f}$$

OVERALL HEAT TRANSFER COEFFICIENT

Desuperheating and Drain Cooling Zones

The overall heat transfer coefficient for the desuperheating and drain cooling zones is calculated by taking the inverse of the sum of the heat transfer resistances given in Eq. 7 (Bell, 1986):

$$\frac{1}{U}=\frac{1}{h_o}+R_{fo}+\frac{\Delta x_w A_o}{k_w A_m}+\frac{A_o}{h_i A_i} \quad (8)$$

where R_{fo} is the outside fouling resistance taken as 5.283×10^{-5} m^2 °C/kW (0.0003 $hrft^2$ °F/Btu).

Condensing Zone

The overall heat transfer coefficient for the condensing zone is calculated by inverting the sum of the heat transfer resistances using the method of Clemmer and Lemezis (1965):

The tube-side convective resistance R_h is calculated using:

$$\frac{1}{R_h}=\frac{h_i D_i}{D_o} \quad (9)$$

The tube-side conduction resistance R_w is calculated using:

$$R_w=\frac{tD_o}{kD_m} \quad (10)$$

The tube-side fouling resistance is obtained from:

$$R_{ts}=3.522 \times 10^{-5}\frac{D_o}{D_i}\frac{m^2\ °C}{kW}\ \left(0.0002\frac{D_o}{D_i}\frac{hrft^2\ °F}{Btu}\right) \quad (11)$$

The total resistance is the sum of the above resistances:

$$R_f=R_c+R_h+R_w+R_{ts} \quad (12)$$

where R_c is the shell-side heat transfer coefficient obtained previously. The condensing zone heat transfer is the inverse of R_t:

$$U = \frac{1}{R_t} \tag{13}$$

PRESSURE DROP ANALYSIS

Desuperheating Zone

The method calculates two kinds of pressure drops and sums them over the entire zone length. The pressure drop ΔP_b is the pressure in one crossflow section if there is no leakage or bypass flow. The pressure drop ΔP_w is the pressure drop in one baffle window section if there is no leakage or bypass flow. The crossflow pressure drop is given by (Bell, 1986):

$$\Delta P_b = \frac{2 f_i \, m_g^2 \, N_c}{\rho_s \, g_c \, S_m^2} \tag{14}$$

where f_i is the friction factor plotted versus Re_s in Figure 8 and N_c is the number of tubes in crossflow given by:

$$N_c = \frac{(CM)(A)}{D_{olt}\,(0.866)(P)} = \frac{S_m}{S(P)} \tag{15}$$

The baffle window pressure drop is given by:

$$\Delta P_w = \frac{m_s^2}{g_c \, S_w^2 \rho_s} \tag{16}$$

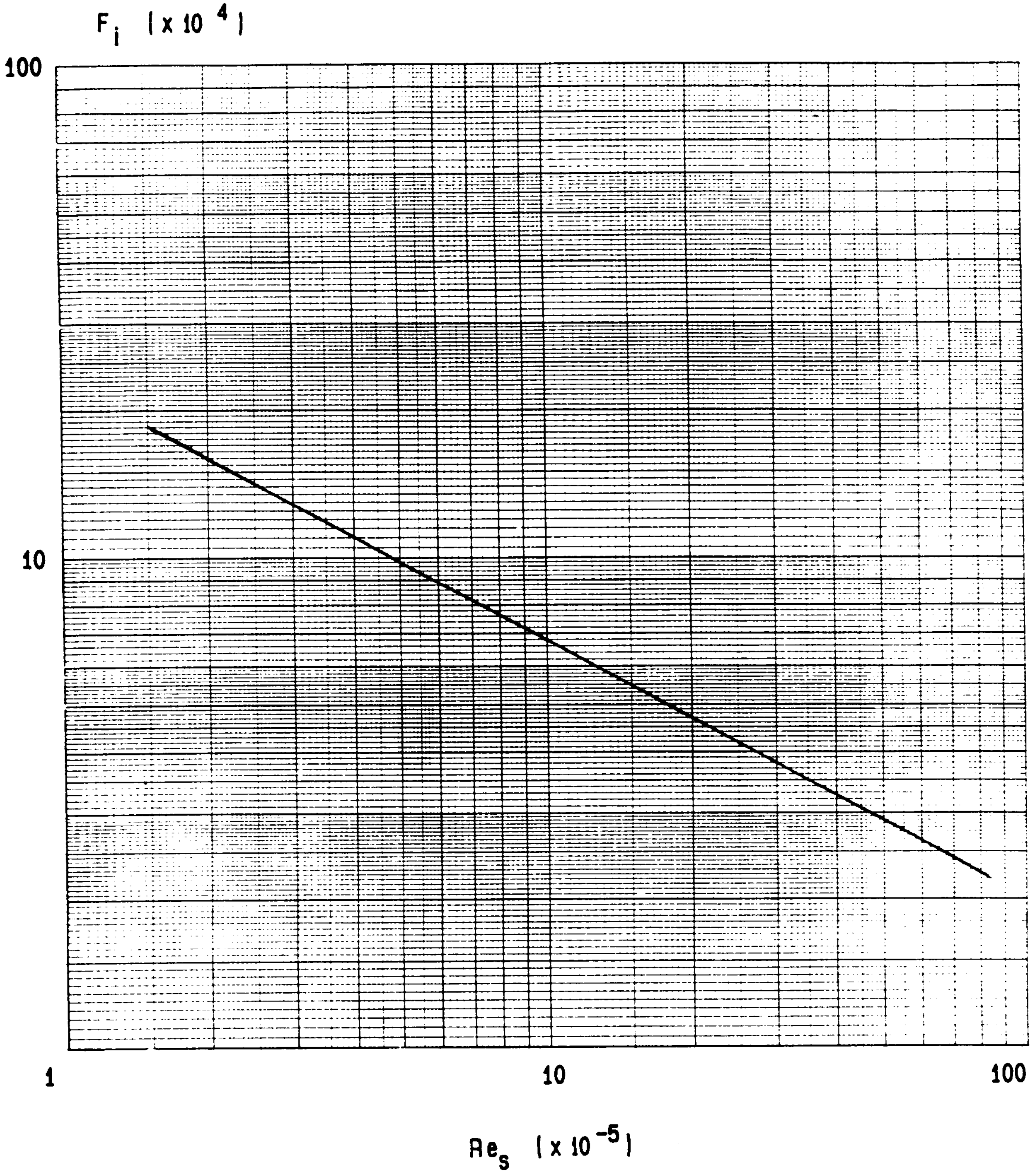

Figure 8: Pressure Drop Correction Factor For the Desuperheating Zone

These pressure drops are then corrected for leakage, bypass, and baffle spacing using J_l,J_b, and J_s, respectively using:

$$\Delta P_s = \left(\left(N_b - 1\right)\Delta P_b J_b + N_b \, \Delta P_w\right) J_l + 2\Delta P_b J_b J_s \tag{17}$$

where N_b is the number of baffles given by:

$$N_b = \frac{L - L_{si} - L_{so}}{L_s} + 1 \tag{18}$$

Condensing Zone

The pressure drop in the condensing zone is negligible and assumed equal to zero.

Drain Cooling Zone

The drain cooling zone pressure drop is calculated using the same equations as the desuperheating zone except for the baffle window pressure drop, DP_w(Bell, 1986):

$$\Delta P_w = \frac{m_s^2}{g_c \, S_m \, S_w \, \rho_s} \tag{19}$$

The correction factor f_i for this zone is obtained in Figure 9.

CALCULATION OF FEEDWATER OUTLET TEMPERATURE

After the heat transfer coefficient and pressure drop for each zone has been obtained, the last task in evaluating the feedwater heater design performance is to calculate the feedwater outlet temperature and compare it to the value that is guaranteed by the heater manufacturer. The

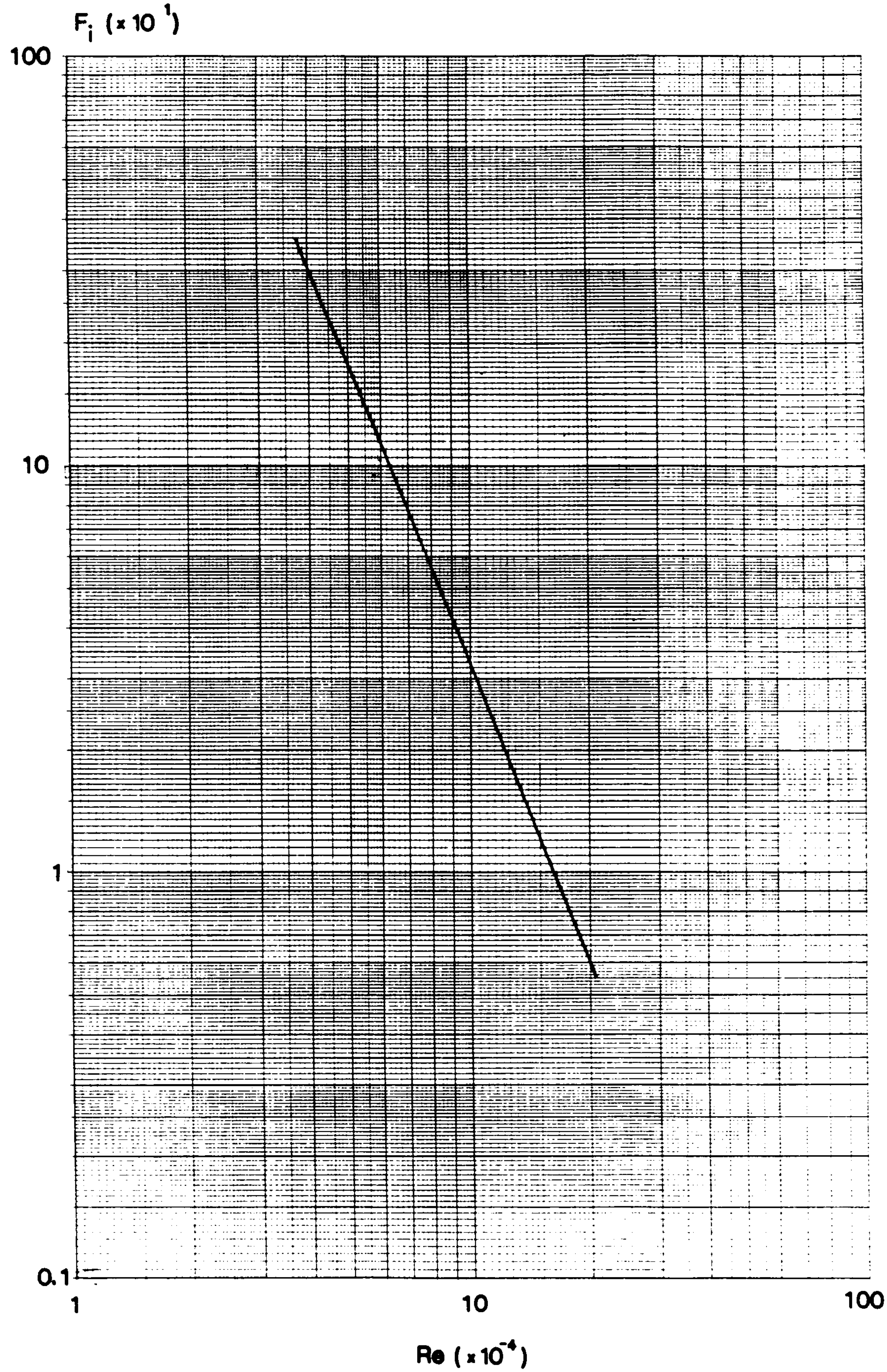

Figure 9: Pressure Drop Correction Factor For the Drain Cooling Zone

feedwater outlet temperature from the heater is calculated by obtaining an energy balance in each zone using the following equation:

$$Q = m_s (h_{si} - h_{so}) = m_{fw} (h_{fwo} - h_{fwi}) = U(A) \Delta T_{lm} (F) \qquad (20)$$

where:

- U = the calculated overall zone heat transfer coefficient
- A = the calculated total zone area
- ΔT_{lm} = the log mean temp. difference
- F = the log mean temp. difference correction factor.

This is an iterative process that is explained in detail in Refs. 8 and 9. The entire process has been incorporated into the PEPSE Program.

Terminal Temperature Difference and Drain Cooler Approach

The utility normally purchases a feedwater heater by specifying a terminal temperature difference(TTD) and drain cooler approach (DCA). The TTD is defined as the saturation temperature at the extraction steam inlet pressure minus the feedwater outlet temperature:

$$TTD = T_{sat,ext} - T_{fwo} \qquad (21)$$

The drain cooler approach is defined as the drain cooler condensate outlet temperature:

$$DCA = T_{co,dc} - T_{fwi} \qquad (22)$$

APPLICATION OF METHOD

The following example applies and illustrates the theory described previously for an actual feedwater heater design. The design is courtesy of Marley Heat Transfer Corporation (Biar, 1992).

A 570 MW coal fired steam generating unit requires a new feedwater heater. The existing heater which has copper-nickel tubes is beyond its useful life. The utility has specified that the new heater be designed with type 304 stainless steel tubes for better long term corrosion resistance. The thermal requirements for this heater are a TTD of -1.67 °C (-3.00 °F) and a DCA of 5.56 °C (10.0 °F). Heater design data available from the manufacturer are listed in Table 1, and detailed baffle information is shown in Figure 10.

PEPSE Modeling

To utilize PEPSE for the heater evaluation the feedwater heater design mode is selected using the "JW Method". The feedwater heater described above is a Type 18. A PEPSE model is constructed for this heater as is currently done for other design mode calculations. All streams and components are identified as shown in Figure 11.

Data Inputs to PEPSE

The following is a list of required inputs to PEPSE for design evaluation (Minner, 1994). Data inputs are explained in detail in Volume I of the manual.

General Data

Diameter at tube outer limit (D_{otl}):	152.4 mm	(60. in)
Tube inside diameter:	1.221 mm	(0.4807 in)
Tube outside diameter:	1.588 mm	(0.625 in)

TABLE 1

FEEDWATER DESIGN SPECIFICATION SHEET FOR HEATER 1

	Shell Side		Tube side
Fluid Circulated	Steam	Drains	Feedwater
Fluid Entering kg/sec(lb/hr)	42.791(338907.30)		455.6239(3,616,063)
Inlet Enthalpy kJ/kg(Btu/lb)	3054.26(1314.00)		883.78(380.22)
Outlet Enthalpy kJ/kg(Btu/lb)		900.96(387.61)	1085.59(467.04)
Inlet Temperature °C(°F)	333.16(631.69)		205.11(401.20)
Saturation Temperature °C(°F)	247.93(478.27)		
Outlet Temperature °C(°F)		210.67(411.20)	249.61(481.30)
Operating Pressure kPa(psia)	3840.40(557.00)		22752.8(3300.0)
Pressure Drop kpa(psia)	DSH 10.41(1.51)	DC 26.34(3.82)	68.95(10.0)
Number of Passes			2

Desuperhtg., Condensing and Drain Cooling Zones

Zone	Heat Exchanged MW(MMBtu/hr)	Effective Area m^2 (ft^2)	LMTD °C(°F)	Heat Trans. Coefficient $W/m^2 \cdot C(Btu/hrft^2 \cdot F)$	Baffle Spacing cm(in)	Baffle Type
Desup.	9.0694(30.9664)	402.92(4337.0)	39.48(71.06)	570.11(100.47)	23.338(9.188)	Multi
Cond.	75.4672(257.6728)	1824.89(19643)	13.09(23.57)	3157.92(556.51)	92.87(36.563)	N/A
D.C.	7.4165(25.3228)	208.16(2240.0)	16.56(29.80)	2151.77(379.20)	28.100(11.063)	Single

Tube Material: Stainless Steel

Number of Tubes: 2325

D_{otl} m(ft) 1.524(5.000)

Tube Outer Diameter cm(in) 1.588(0.625)
Tube Wall Thickness cm(in) 0.1829(0.072)
Tubing Pitch cm(in) 2.1432(0.8438)

Overall Performance

TTD	°C(°F)	-1.67 (-3.00)
DCA	°C(°F)	5.56(10.00)

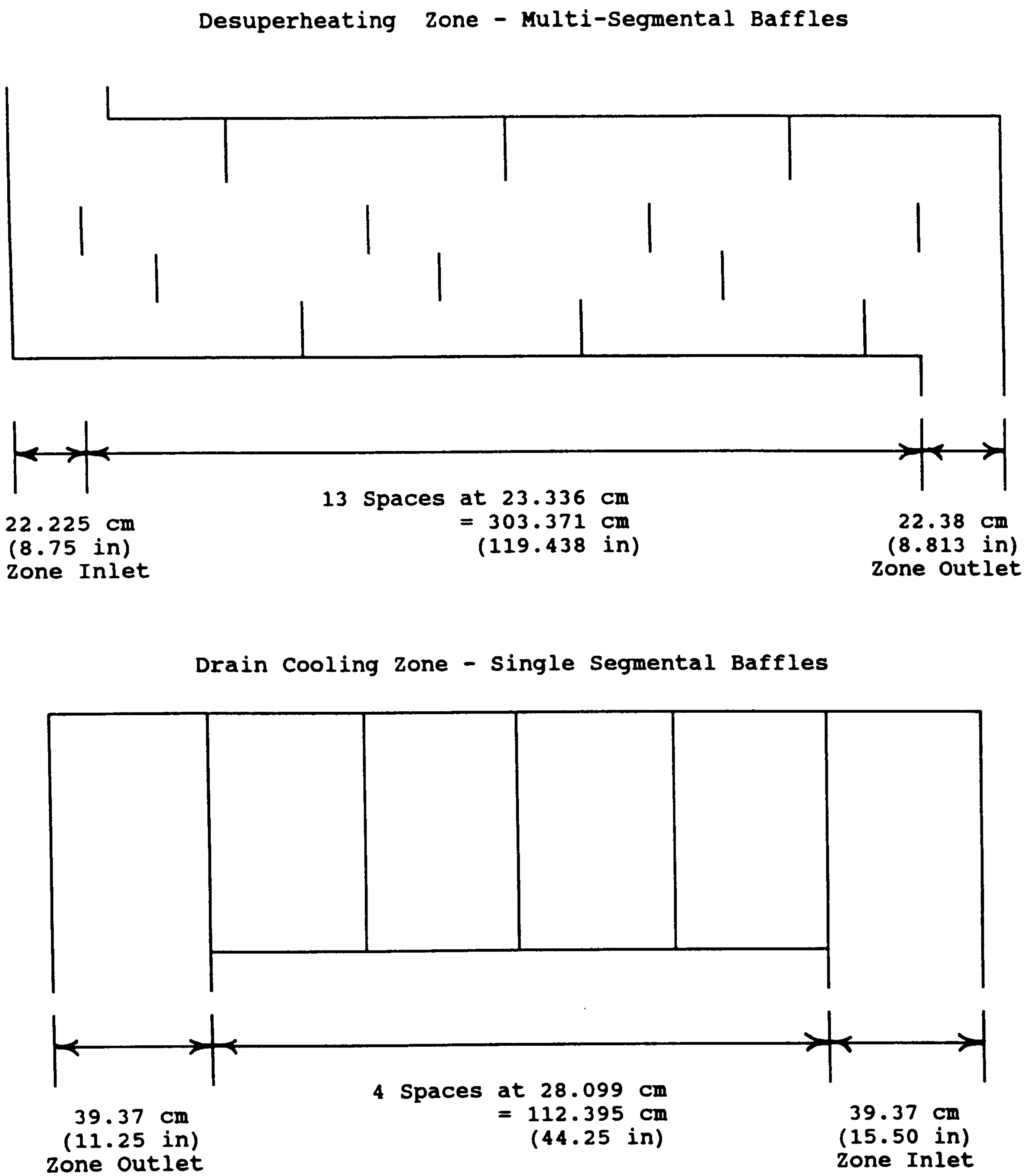

Figure 10: Baffle Dimensions

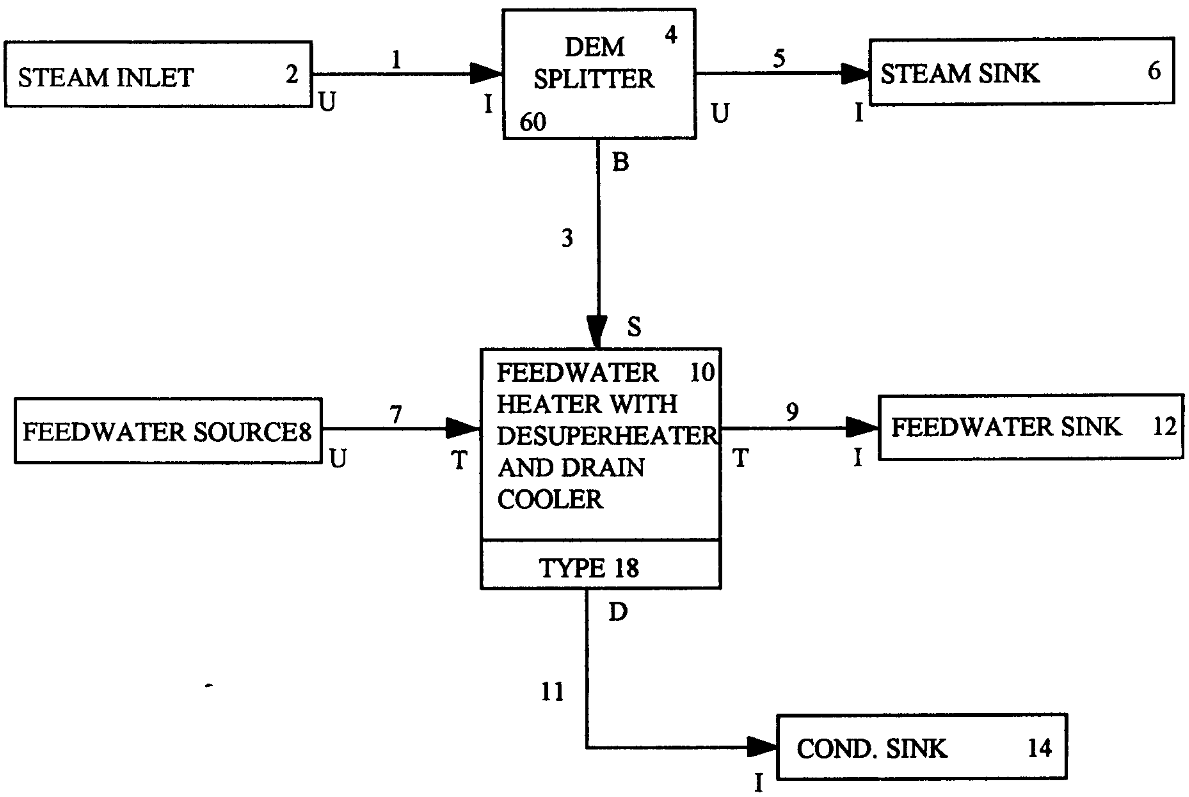

Figure 11: PEPSE Model For a Type 18 Feedwater Heater

Number of tubes:	2325	
Thermal conductivity:	17.815 W/m °C	(10.29 Btu/hr-ft^2 °F)
Tube pitch:	2.1433 cm	(0.8438 in)

<u>Condensing Zone</u>

Tube length:	1573.86 cm	(619.63 in)
Tube inside fouling resistance:	3.522x10^{-5} m^2 °C/W	(0.0002 hr-ft^2 °F/Btu)
Tube outside fouling resistance:	0.0 m^2 °C/W	(0.0 hr-ft^2 °F/Btu)

<u>Desuperheating Zone</u>

Baffle segmentation Description:	Multi-segmental	
Intermediate baffle average spacing:	23.338 cm	(9.188 in)
Number of baffles:	14	
Average baffle spacing ratio:	0.96	
Baffle window area:	0.7075 m^2	(7.616 ft^2)
Zone overall tube length:	347.5 cm	(136.81 in)
Tube inside fouling resistance:	0.0 m^2 °C/W	(0.0 hr-ft^2 °F/Btu)
Tube outside fouling resistance:	5.283x10^{-5}m^2 °C/W	(0.0003 hr-ft^2 °F/Btu)

<u>Drain Cooling Zone</u>

Baffle segmentation description:	Single	
Intermediate baffle average spacing:	28.099 cm	(44.25 in)
Number of baffles:	5	
Average Baffle spacing ratio:	1.2	
Baffle window area:	0.173 m^2	(1.862 ft^2)
Zone overall tube length:	179.45 cm	(70.65 in)
Tube inside fouling resistance:	0.0 m^2 °C/W	(0.0 hr-ft^2 °F/Btu)
Tube outside fouling resistance:	5.283x10^{-5} m^2 °C/W	(0.0003 hr-ft^2 °F/Btu)

This is all of the required data to execute a PEPSE heater design model. All of the data are available from the heater manufacturer. After all data are entered the model was executed.

PEPSE Results

The following results were calculated by PEPSE. Iterations resulted in a steam mass flow rate of 42.862 kg/hr (340,179 lb/hr).

Drain Cooling Zone

$U = 2220.4$ W/m^2 °C	(391.3 Btu/hrft^2 °F)		
$h_{si} = 1074.1$ kJ/kg	(462.1 Btu/lbm)	$T_{si} = 247.8$ °C	(478.0 °F)
$h_{so} = 900.5$ kJ/kg	(387.4 Btu/lbm)	$T_{so} = 210.6$ °C	(411.1 °F)
$h_{fwi} = 883.8$ kJ/kg	(380.2 Btu/lbm)	$T_{fwi} = 205.2$ °C	(401.3 °F)
$h_{fwo} = 900.0$ kJ/kg	(387.2 Btu/lbm)	$T_{fwo} = 208.8$ °C	(407.9 °F)
$\Delta T_{lm} = 17.0$ °C	(30.6 °F)		
$F = 0.946$			
$Q_{dc} = 7.442\text{x}10^3$ kw	(25.410x10^6 Btu/hr)		

Condensing Zone

$U = 3249.2$ W/m^2 °C	(572.6 Btu/hrft^2 °F)		
$h_{si} = 2836.3$ kJ/kg	(1220.2 Btu/lbm)	$T_{si} = 258.2$ °C	(496.7 °F)
$h_{so} = 1074.1$ kJ/kg	(462.1 Btu/lbm)	$T_{so} = 247.8$ °C	(478.0 °F)
$h_{fwi} = 900.0$ kJ/kg	(387.2 Btu/lbm)	$T_{fwi} = 208.8$ °C	(407.9 °F)
$h_{fwo} = 1066.0$ kJ/kg	(458.6 Btu/lbm)	$T_{fwo} = 245.6$ °C	(474.1 °F)
$\Delta T_{lm} = 12.72$ °C	(22.89 °F)		
$Q_{cond} = 7.5535\text{x}10^4$ kw	(257.905x10^6 Btu/hr)		

Desuperheating Zone

$U = 626.5\ W/m^2\ °C$	$(110.4\ Btu/hr\text{-}ft^2\ °F)$		
$h_{si} = 3054.3$ kJ/kg	(1314.0 Btu/lbm)	$T_{si} = 333.2$ °C	(631.7 °F)
$h_{so} = 2836.3$ kJ/kg	(1220.2 Btu/lbm)	$T_{so} = 258.2$ °C	(496.7 °F)
$h_{fwi} = 1066.0$ kJ/kg	(458.6 Btu/lbm)	$T_{fwi} = 245.6$ °C	(474.1 °F)
$h_{fwo} = 1086.5$ kJ/kg	(467.4 Btu/lbm)	$T_{fwo} = 250.0$ °C	(482.0 °F)
$\Delta T_{lm} = 37.39$ °C	(67.3 °F)		
F = 0.9933			
$Q_{ds} = 9.337\times10^3$ kw	$(31.879\times10^6$ Btu/hr)		

TTD and DCA

Using the data above PEPSE calculated a TTD and DCA of -2.08 °C (-3.74 °F) and 5..44 °C (9.8 °F) respectively for this heater. These values are better than the guaranteed values of -1.67 °C and 5.56 °C. Therefore this heater design meets guaranteed specifications and is acceptable.

CONCLUSION

This paper has explained and applied the Modified Delaware Method for validating feedwater heater performance using PEPSE. The Method enables a utility to verify that a feedwater heater meets specifications before it is purchased. When PEPSE is utilized, this task takes only one to three hours including data input. This makes it a very valuable and efficient performance prediction tool.

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NOMENCLATURE

A = area

A_i = inner area

A_m = mean area

A_o = outer area

CM = cross flow multiplier

C_f = tube-side specific heat

C_s = shell-side specific heat

D_i = inner diameter

D_o = outer diameter

D_{otl} = outer tube limit

f_i = correction factor

h_{fg} = latent heat of condensation

h_{fwi} = feedwater enthalpy at heater inlet

h_{fwo} = feedwater enthalpy at heater outlet

h_i = tube-side heat transfer coeff.

h_o = shell-side heat transfer coeff.

h_{si} = shell-side inlet enthalpy

h_{so} = shell-side outlet enthalpy

J_b = bypass correction factor

J_c = crossflow correction factor

J_f = Colburn j factor

J_l = leakage correction factor

J_s = baffle spacing correction factor

k_f = feedwater thermal conductivity

k_s = steam thermal conductivity

k_w = wall thermal conductivity

L = zone length

$L_{s,si,so}$ = baffle spacing, avg, at zone inlet and outlet respectively

m_s = steam mass flow rate

N_c = Number of tubes in crossflow

P = pitch

Pr = Prandtl Number

St = Stanton Number

Q_s = shell side heat transfer

R_c = cond. heat transfer resis

Re = Reynolds Number

R_{fo} = shell-side fouling resis

R_t = Total resistance

R_{ts} = tube-side fouling resis

R_w = tube wall resistance

S = Baffle spacing

S_m = cross flow area

t = thickness

T_{si} = Shell-side inlet temp.

T_{so} = Shell-side outlet temp.

U = zone heat transfer coeff.

ΔP_b = baffle pressure drop

ΔP_w = window pressure drop

ΔT_{lm} = log mean temp. diff.

μ_s = steam viscosity

μ_f = feedwater viscosity