CICIND

MANUAL FOR THERMOFLUODYNAMIC DESIGN OF CHIMNEYS AND CHIMNEY LINERS

August 2001

ISBN 1-902998-12-X

Office of the Secretary, 14 The Chestnuts, Beechwood Park, Hemel Hempstead, Herts., HP3 0DZ, UK
Tel: +44 (0)1442 211204 Fax: +44 (0)1442 256155 e-mail: secretary@cicind.org

TABLE OF CONTENTS

Committee Members

Mario Poli, Chairman	Italy
Georg Berger	Germany
John Davenport	Great Britain
Friedhelm Henseler	Germany
Raymond Warren	USA

INTRODUCTION

CICIND formed a Committee in 1995 to write a Manual of design considerations for chimney pressure losses and draught, for heat transfer and heat losses, and for other associated matters.

This Manual is presented for use by engineers who are experienced in the modern design of chimneys, but who may not have detailed information available on fluodynamics.

There are many reference books which give factors and formulae which sometimes differ widely. This is particularly true for flow loss factors and heat transfer factors. The Committee has used the information which is familiar to its members and it is believed that these produce acceptable chimney designs. The discrepancies between different data sources might be resolved by additional testing or field data.

Data from any other sources may be used, provided that it can be reasonably shown to be valid for the intended use.

Users are cautioned that relatively small changes in the physical conditions can sometimes lead to large changes in flow loss factors. This is particularly true at bends and junctions.

Any reader who finds data on any aspect is invited to send it to CICIND, whether it confirms or disagrees with the data here. It is expected that Owners in particular may have access to useful information which could be incorporated in future revisions.

NEED

The mechanical design aspects of a chimney are sometimes overshadowed by the structural design aspects. Chimney draught and heat transfer performance at the mandated chimney height are a vital part of the overall chimney design. A manual giving accepted thermofluodynamic design considerations for concrete and steel chimneys with their liners is needed by the chimney designer.

SCOPE

This manual provides in three sections the generally accepted methods for calculating (a) chimney draught and draught losses; (b) chimney heat losses; and (c) other chimney mechanical design considerations. These include: (1) annulus pressurisation; (2) gas acid dew point; and (3) thermal expansion. The formulae, tables and figures are applicable for both concrete and steel chimneys with their liners or linings.

The information given for thermofluodynamics of chimneys should be used in conjunction with the information in other CICIND publications for the complete design of chimneys.

Note that pressures are calculated in terms of the head of water throughout this Manual so their units are mmH_2O. To convert to Pascals multiply by 9.81.

2.0 REFERENCES

1 H. Rietschel - W. Raiss
Conditioning and Combustion Engineering (handbook)
Springer-Verlag (Berlin), 1970

2 i.e. Idelchik
Handbook of Hydraulic Resistance
Begell house, inc (New York), 1996

3 E. Hampe
Induustrial Chimneys (handbook)
Veb verlag für baumwesen (Berlin), 1969

4 ASME STS-1
American Society of Mechanical Engineers
Steel Stack Standard, (New York), 1992

5 TC 297/WG1
European Committee for Standardisation
Working Group 1

6 ACI 307-95 (and ACI 307 R-95)
Standard practice for the design and construction of
reinforced concrete chimneys and commentary.
American Concrete Institute (Detroit) - 1995

7 K.K.H. Kämmer
Flue gases flow section
Technische mitteilungen (Germany) - 1980

8 F.H. Norton
Refractories (handbook)
Mc Graw - Hill Book Company, Inc. 1949

9 F. Henseler
Desulphurization systems regarding operational
conditions of chimneys
CICIND Report, Vol. 3, No. 2, Autumn 1987

10 H. Vial
Use of refractory products (handbook)
Syndacat National des Entrepreneurs et Constreuers en
Thermique Industrielle, (Dourdan, France), 1986

SECTION A

SYMBOLS

A - Duct inlet area (m^2)

b_0 - Duct size (m)

d - Flow hydraulic diameters (m)

f - Friction coefficient (dimensionless)

g - Acceleration due to gravity (9.81 m/s^2)

G - Rate (kg/sec)

h_{loss} - Pressure (head) loss (mm of water [mmH_2O])

H_T - Chimney or chimney liner height at exit (m)

H_E - Centreline elevation of inlet duct (m)

J - Joule (J)

K - Local coefficient (dimensionless)

L - Flue gas path (m)

p , P - Pressure (mm of water [mmH_2O])

Q - Volume flow rate (m^3/s)

R,r - Bend radius (m)

R_e - Reynolds number (dimensionless)

R_L - Gas constant (J/kg. K)

S - Duct area (m^2)

t - Temperature (°C)

T - Temperature (°K)

v - Velocity (m/sec)

V - Rate (Nm^3/sec)

α - Angle between duct and chimney or chimney liner axis (degree) or change of shape of liner

Δp - Pressure difference (mm of water [mmH_2O])

η - Dynamic viscosity (kg/m sec)

ρ - Density (kg/m^3)

NOTE: The formulae for pressure given in the following sections are expressed in terms of 'head' and have the units of 'mm of water' or mmH_2O. To convert to units of Pascals (Pa), multiply by 9.81 (= g)

1. DATA REQUIRED

1.1. Ambient Conditions

- Maximum temperature
- Minimum temperature
- Design temperature
- Maximum pressure
- Minimum pressure
- Design pressure

1.2. Flue Gases

- Standard density, or molecular weight, or chemical analysis
- Maximum operating temperature
- Out of service temperature (if any)
- Minimum operating temperature
- Design temperature
- Rate
- (Required) pressure condition at inlet
- Minimum exit velocity (if any)
- Duct section at the interface between chimney flange and duct.
- Inlet duct centre-line elevation.

2. NATURAL DRAUGHT

$$(\rho_{air} - \rho_{gases}) \times [H_T - H_E] \quad \textbf{[A.a]}$$

With velocity $\geq$ 15 m/s and/or with chimneys or chimney liners sufficiently insulated, the temperature drop from inlet to top is very limited (0.5 - 1.5° C) and, therefore, the temperature of the flue gas may be assumed equal to the inlet one when formula [A.a] is applied. More exact calculation of the temperature loss may be carried out following the considerations of Section B.

In case of low velocity, and/or chimneys or chimney liners not being insulated, the temperature drop may be much higher and must be evaluated through the considerations of Section B.

Formula [A.a] will be applied to check, at least:

- Minimum available draught
- Maximum available draught (data required to consider circumferential pressure, or in case of steel inlet, or for compensator selection).

3. PRESSURE LOSSES

3.1. Friction losses

To be evaluated from:

$$\frac{f \times L}{d} \times \frac{v^2 \rho}{2g} \quad \textbf{[A.b]}$$

The value of the "*f*" may be obtained from Fig. A1 where:

$$R_e = \frac{v \times \rho \times d}{\eta} \qquad \textbf{[A.c]}$$

In the usual operating conditions of industrial chimneys a variation in the R_e value only slightly influences the *f* factor. A precise evaluation of the dynamic viscosity is unnecessary, and the following values may be adopted:

at 100° C	$\eta = 2.04 \times 10^{-5}$	kg/m sec
at 150° C	$\eta = 2.18 \times 10^{-5}$	kg/m sec
at 200° C	$\eta = 2.31 \times 10^{-5}$	kg/m sec
at 300° C	$\eta = 2.55 \times 10^{-5}$	kg/m sec

In Fig. A1 the roughness is expressed in terms of relative roughness (i.e. ratio between absolute roughness and liner diameter). The following values of absolute roughness are suggested:

Brick liner: .... 5 mm

Steel liner: .... 2 mm

GRP liner: ....… ..2 mm

Actual roughness, however, is influenced by the quality of installation, by local deposits or erosion or corrosion by flue gases, by brick shape etc.

3.2. Velocity variation losses

3.2.1. Inlet losses

3.2.1.1. Arrangement following Fig. A2: ($S_3 = S1$)

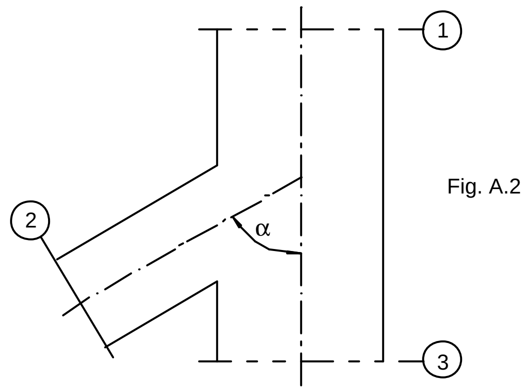


Figure A2

Loss from section 2 to section 1:

$$h_{loss} = K_c \times \frac{v_2^2}{2 \cdot g} \times \rho_2 \qquad \textbf{[A.d]}$$

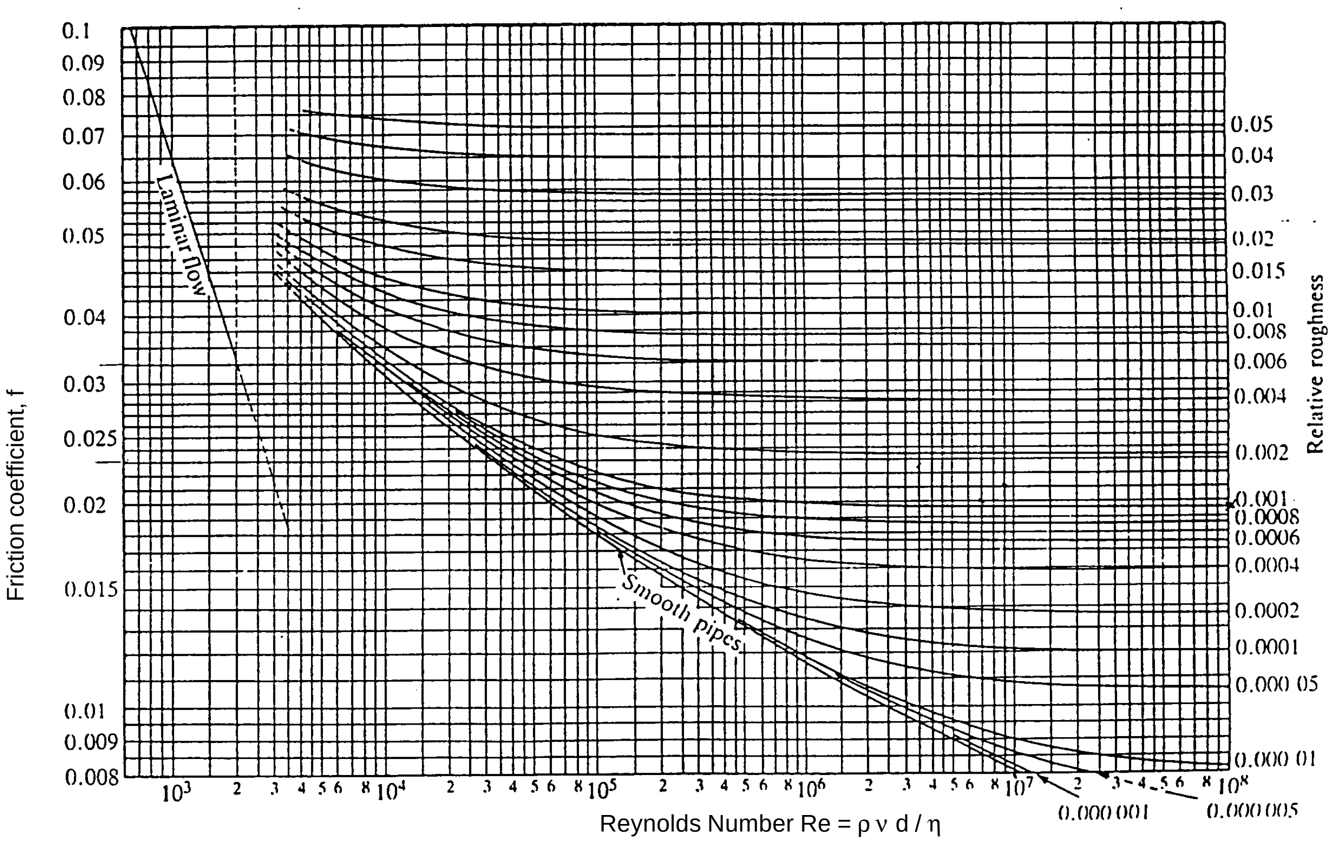


Figure A1 - Friction factor

Loss from section 3 ($v_3 > 0$) to section 1: The following formula will be applied:

$$h_{loss} = K_d \times \frac{{v_3}^2}{2 \cdot g} \times \rho_3 \qquad \textbf{[A.e]}$$

Values of local coefficients "K" to be used in Formulas (A.d) and (A.e) and given hereunder are suggested values; the designer may use other values when available from reliable sources.

For Formula [A.d]:

$$K_c = A_c \times \left[1 + \frac{\rho_1}{\rho_2}\left(\frac{v_1}{v_2}\right)^2 - 2\frac{\rho_3}{\rho_2}\left(\frac{v_3}{v_2}\right)^2 - 2\frac{S_2}{S_1}\cos\alpha \right]$$

[A.d1]

The values of the coefficient A_c to be introduced in Formula (A.d1) are shown in Table A1:

For Formula [A.e]:

$$K_d = \left(\frac{v_1}{v_3}\right)^2 \cdot \frac{\rho_1}{\rho_3} - \left[1 + 2\left(\frac{v_2}{v_3}\right)^2 \frac{\rho_2}{\rho_3}\left(\frac{S_2}{S_1}\right)\cos\alpha \right]$$

[A.e1]

3.2.1.2. *Two ducts at the same level and $v_4 = 0$*

Note: The use of partition walls is not recommended by CICIND and has not, therefore, been examined.

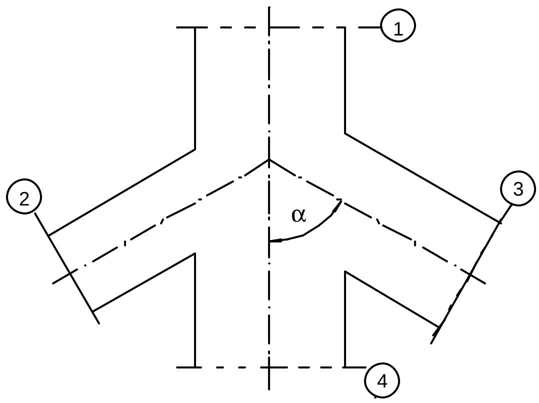


Figure A3

Loss from section 3 to section 1:

$$h_{loss} = \frac{\rho_1 \cdot S_1 \cdot v_1^2 - \left(\rho_3 \cdot S_3 \cdot v_3^2 + \rho_2 \cdot S_2 \cdot v_2^2\right)\cos\alpha}{g \times S_1} - \frac{\left(\rho_3 \cdot v_3^2 - \rho_2 \cdot v_2^2\right) \cdot S'_2 \cdot \sin\alpha \cdot \cos\alpha}{g \times S_1} \qquad \textbf{[A.f]}$$

Loss from section 2 to section 1:

$$h_{loss} = \frac{\rho_1 \cdot S_1 \cdot v_1^2 - \left(\rho_3 \cdot S_3 \cdot v_3^2 + \rho_2 \cdot S_2 \cdot v_2^2\right)\cos\alpha}{g \times S_1} - \frac{\left(\rho_2 \cdot v_2^2 - \rho_3 \cdot v_3^2\right) \cdot S'_3 \cdot \sin\alpha \cdot \cos\alpha}{g \times S_1} \qquad \textbf{[A.g]}$$

S_2/S_1	≤ 0.35	> 0.35	> 0.35
Q_2 / Q_1	≤ 1.0	≤ 0.4	> 0.40
A_c	1.0	$0.9 \times \left(1 - \frac{Q_2}{Q_1}\right)$	0.55

Table A1 - Values of A_C coefficient

Where:

$$S'_2 = \frac{Q_2}{v_1} \quad \text{and} \quad S'_3 = \frac{Q_3}{v_1}$$

In the most usual cases where:

$v_2 = v_3$ and $S_2 = S_3$ and $\rho_2 = \rho_3 = \rho$

$$h_{loss} = \left[2 \times \frac{S_2}{S_1}\left(\frac{S_2}{S_1} - 2\cos\alpha\right)\right] \times \frac{v_2^2}{2g} \times \rho$$

3.2.1.3. *Connection through 90° bend*

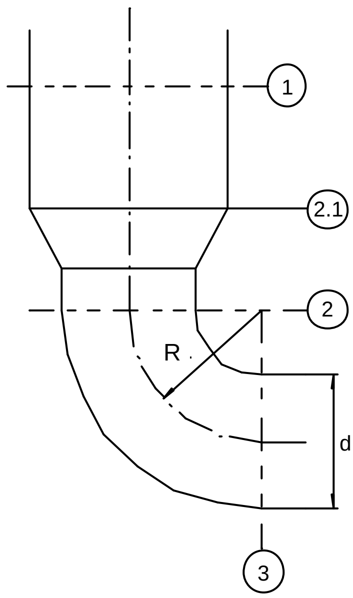


Figure A4

For $S_3 = S_2$ the following formula will be applied to calculate local loss in the bend:

$$h_{loss} = K_g \times \frac{{v_3}^2}{2g} \times \rho \qquad \textbf{[A.h]}$$

The "K_g" values for formula (A.h) are in Table A2:

3.2.1.4 *Turning vanes*

When the ratio between the bending radius of a 90° curve and its diameter (or its height for rectangular sections) falls below 1.00-0.80, the local pressure loss increases very quickly. In such circumstances the installation of turning vanes will be beneficial (Figure A5). The sizes, pitch and number of these vanes are based on practical data as shown hereunder.

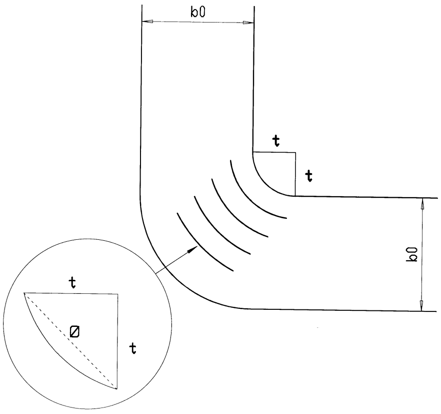


Figure A5

On the assumption of vanes simplified and bent along the surface of a cylinder (ø=90-95°) the following number of vanes is suggested:

(1)	Normal	2.13x (b_o/r)-1
(2)	Reduced	1.40x (b_o/r)-1
(3)	Minimal	0.90x (b_o/r)-1

Pressure losses:

$$h_{loss} = K_{loc} \cdot K_{RE} \cdot \frac{V_o^2}{2g} \cdot \rho \qquad \textbf{[A.i]}$$

The value of coefficient K_{loc} is given in Table A3:

The K_{RE} coefficient is given by:

$$K_{RE} = 0.8 + 4.02 \times \frac{10^4}{R_e}$$

Note: friction losses to be calculated separately.

r/b_0 =	0	0.05	0.10	0.15	0.20	0.25	0.30
Normal	0.42	0.35	0.30	0.26	0.23	0.21	0.20
Reduced	0.42	0.35	0.30	0.24	0.20	0.17	0.14
Minimal	0.57	0.48	0.43	0.39	0.35	0.31	0.28

Table A3—Values of K_{loc}

3.2.2. Losses at discontinuities

The local loss between adjacent liner sections (Fig. A6) where the lower section ends and the upper section starts:

$$h_{loss} = \frac{(v_1 - v_2)^2}{2 \cdot g} \times \rho \quad \textit{for each discontinuity} \qquad \textbf{[A.j]}$$

where v_1 and v_2 are the velocities corresponding to d_1 and d_2.

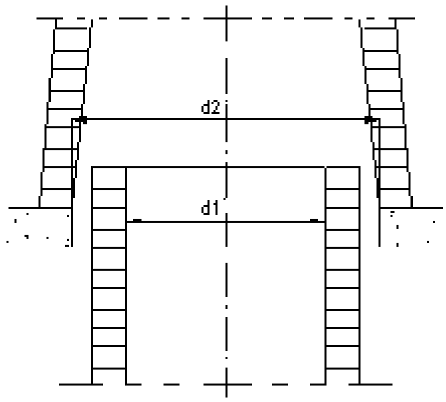


Figure A6

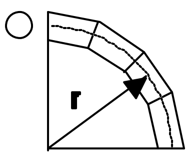
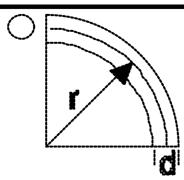
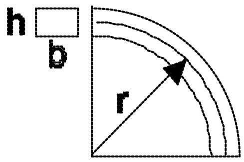
										
r/d	Sections number			r/d	K_g	r/h	b : h			
	3	4	5				0.5	1.0	2.0	4.0
1.0	0.50	0.40	0.35	0.5	0.75	0.5	1.25	1.20	1.00	0.80
1.5	0.40	0.35	0.30	1.0	0.35	0.75	0.50	0.45	0.45	0.55
2.0	0.40	0.30	0.25	1.5	0.30	1.0	0.30	0.30	0.25	0.25
4.0	0.55	0.35	0.30	2.0	0.28	1.5	0.20	0.15	0.10	0.10
				3.0	0.25	2.0	0.20	0.15	0.09	0.08

Table A2 - Values of K_g

3.2.3. Top exit - Local losses

For the case where $S_e \neq S_1$ (see Fig. A.7) the additional losses due to the change in area are:

For the case in Fig. A7(a):

$$h_{loss} = K_i \cdot \frac{v_e^2}{2g} \cdot \rho \qquad \textbf{[A.k]}$$

where:

	$\alpha \leq 10°$		$\alpha = 10° - 50°$	
S_e/S_1	0.3	0.4	0.6	0.8
K_i	≈ 0.00		0.05 - 0.10	

For the case in Fig. A7(b):

$$h_{loss} = K_j \frac{v_1^2}{2g} \times \rho \qquad \textbf{[A.m]}$$

where: for $\propto \underline{<} 8°$:

$$K_j = \left(1 - \frac{S_1^2}{S_e^2}\right) \times 0.15$$

Note: For a divergent exit α > 8° should ideally be avoided since it would cause high pressure losses.

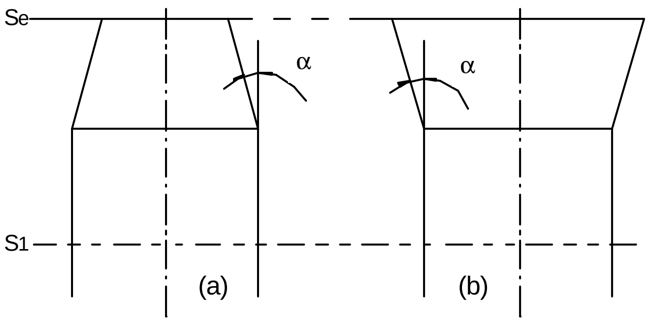


Figure A7 - Exit losses

4. KINETIC ENERGY VARIATION

Pressure requirements calculated through paragraph 3.2.1, 3.2.2 and 3.2.3, include not only local friction (except 3.2.1.4) losses but also the kinetic energy required, if any, between the two sections of reference. The kinetic energy variation, if any, from the referenced section to the top is not included.

The total pressure energy variation shall, therefore, include the term:

$$\frac{v_e{}^2 - v_R{}^2}{2g} \times \rho \qquad \textbf{[A.n]}$$

where:

v_e=	top exit velocity	(m/s)
v_R =	velocity at referenced section	(m/s)

5. PRESSURE CONDITIONS

Since the main interest of such calculations is to compare the local absolute pressure with the atmospheric pressure at the same level (i.e. to know if the relative pressure is positive or negative), the following approach is suggested.

5.1. Inlet pressure condition

The inlet relative pressure p_i is defined by the following formula:

p_i = - natural draught + total pressure requirement **[A.p]**

where the "total pressure requirement" has been calculated as outlined in paragraphs 3 and 4.

5.2. Pressure conditions along the liner

The relative pressure, $^-/_+p_x$, at any level "x" above the lower level of figures A2, A3 and A4 is:

$$p_x = \mp p_1 \pm ?H\left(?_{air} - ?_{gases}\right) \pm ?p_{x/1} \qquad \textbf{[A.q]}$$

where:

ΔH = difference in height between section "1'" and "x"

$\Delta p_{x/1}$ = total pressure requirement from section "x" to "1"

By definition, the relative pressure at the upper level (S_e) of figure A7 is zero.

APPENDICES

A.1. AMBIENT AIR DATA

The external air pressure can be calculated from:

$$P_{air} = P_{STD}\ e^{\frac{(-g \cdot H_T / 2)}{(R_L \cdot T)}} \quad \text{(Note: units are Pa)} \qquad \textbf{[A.r]}$$

where:

- P_{STD} = Air pressure at sea level (101325 Pa, 273 K)
- R_L = Gas constant of air (see Table A4) (J/kg · °K)
- T = Air temperature (°K)
- H_T = Height of chimney above sea level (m)

The corresponding value of ρ is:

$$\rho = P_{air} / R_L \cdot T \qquad \textbf{[A.s]}$$

$R_L = \Sigma$ component i by mass x R_i (see Table A4)

Gas	R_i
N_2	296.66
O_2	259.58
H_2O	461.50
CO_2	187.63
SO_2	126.56

Table A4 - Gas constants

A.2. *Flue gases data*

The data of the single main components of the flue gases at NTP are given in Table A5. Standard density, viscosity and specific heat of the gas mixture will be calculated by totalling the values of Table A5 multiplied by the relevant percentage in weight.

Type of gas	Nitrogen N_2	Carbon dioxide CO_2	Oxygen O_2	Water vapour H_2O	Sulphur dioxide SO_2	Air, dry	Argon
Molecular mass M (kg/kmol)	28.0134	44.0098	31.9988	18.0153	64.0590	28.9627	39.944
Molecular standard volume V_{mol} (m^3/kmol)	22.403	22.261	22.392	22.414	21.856	22.400	22.429
Standard density ρ (kg/m^3)	1.2504	1.9770	1.4290	0.8038	2.9310	1.2930	1.7809
Gas constant R (J/kgK)	296.66	187.63	259.58	461.50	125.56	287.10	-
Dynamic viscosity p (10^5.Pa.s)	1.667	1.370	1.926	0.922	1.170	1.724	2.12
Sutherland constant C	102.0	270.0	126.0	961	306	-	142
Critical temperature T_{ki} (K)	126.2	304.2	154.6	647.3	430.8	132.5	150.5
Specific heat capacity C_p (J/kgK)	1038.7	816.5	914.8	1492.0	1740.0	1004.0	-
Heat conductivity W/(mK)	0.024	0.015	0.024	0.033	0.212 (fluid)	0.024	-

Table A5 - Flue gases data

SECTION B

SYMBOLS

c_p = specific heat of air, (J/kg °K)

C_g = specific heat of flue gas, (J/kg °K)

D_b = mean diameter of liner wall, (m)

D_{bi} = inside diameter liner, (m)

D_c = mean diameter of concrete chimney shell, (m)

D_{ce} = outside diameter of concrete chimney shell, (m)

D_i = mean diameter of insulation, (m)

D_s = mean diameter of space between lining & shell, (m)

G = ventilation air mass flow rate, (kg/h)

G_g = flue gas rate, (kg/h)

K = overall heat transfer coefficient, (w/m^2 °K)

K_1 = coefficient of heat transmission from gas to inner surface of liner, (w/m^2 °K)

K_2 = coefficient of heat transmission from outside surface of chimney shell to surrounding air, (w/m^2 °K)

K_r = coefficient of heat transfer between outside surface of liner and inside surface of s hell for chimneys with ventilated air spaces, (w/m^2 °K)

K_s = coefficient of heat transfer between outside surface of liner and inside surface of shell for chimneys with unventilated air spaces, (w/m^2 °K)

L = liner length, (m)

Q = heat flow, (W)

r_q = ratio of heat transmission through chimney shell to heat transmission through lining for chimneys with ventilated air spaces

S = surface area, (m^2)

t_b = thickness of wall of liner without insulation, (m)

t_c = thickness of concrete shell, (m)

t_i = thickness of insulation, (m)

T = temperature of gas inside chimney, (°C, °K)

T_o = temperature of outside air around chimney, (°C, °K)

T_{ao} = maximum ventilation air temperature, (°C, °K)

T_{be} = external surface liner temperature, (°C, °K)

T_{bi} = internal surface liner temperature, (°C, °K)

T_{ci} = internal surface shell temperature, (°C, °K)

T_{ce} = external surface shell temperature, (°C, °K)

T_{ii} = internal surface insulation temperature, (°C, °K)

T_{ie} = external surface insulation temperature, (°C, °K)

$\propto_c$ = coefficient of heat transfer by convection between the external surface of the (insulated) liner and ventilation air, (w/m^2 °K)

$\propto_{c1}$ = as above between ventilation air and internal concrete surface, (w/m^2 °K)

$\propto_{irr}$ = coefficient of heat transfer by radiation between outside surface of (insulated) liner and inside surface of concrete chimney shell, (w/m^2 °K)

λ_c = coefficient of thermal conductivity of the concrete of chimney shell (1.29 w/m °K)

λ_i = coefficient of thermal conductivity of insulation, (w/m °K)

λ_b = coefficient of thermal conductivity of liner, (w/m °K)

1. PURPOSES

1.1 Reinforced concrete chimneys

Thermal calculations may be required to establish the following:

- Thermal gradients of chimney components
- Maximum temperature of reinforced concrete
- Maximum steel liner temperature and minimum steel liner temperature (to be compared with flue gas dew point)
- Loss of temperature in flue gases
- Control of the limit temperatures for materials such as electrical cables, bearing pads, paints, insulating materials etc.
- Accessibility of air space

Note: This last aspect is usually imposed by fixing a maximum ΔT of the ventilation air and/or a maximum "touch" temperature of the external surface of the insulated liner.

A reinforced concrete chimney may be designed with:

a) unventilated air space
b) ventilated air space, accessible or not
c) internal brick liner(s)
d) internal steel liner(s)
e) internal GRP liner(s)
f) external insulation of liner(s) or liners uninsulated
g) internal lining or coating to liners

1.2 Steel chimneys

The thermal gradient through the different material layers of steel chimneys is of primary concern to allow the chimney designer to insure that the minimum metal temperature exposed to the flue gases is constantly above the acid dew point temperature under most operating system loads and ambient conditions.

A steel chimney may be designed with

a) No external or internal heat loss protection
b) External lagging only (sometimes called cladding)
c) External insulation and lagging
d) Internal lining or coating system
e) Dual wall or multi-flue with no insulation between the flue and the outer shell
f) Dual wall or multi-flue with insulation between the flue and the outer shell
g) Single wall for wet gas service

Only for special designs is the air space between the flue and the shell positively ventilated. It is therefore, generally assumed to be dead air with no movement.

1.3 General

The factors effecting the loss of heat through the walls of chimney with its external and internal treatment include:

a) Ambient temperature
b) Ambient wind velocity
c) External film coefficient
d) Internal film coefficient
e) Insulation thermal properties
f) Air space thermal property
g) Internal coating thermal properties
h) Solar intensity

2. CALCULATIONS

2.1 Reinforced concrete chimneys

The heat balance is:

$$Q_L + Q_s = Q_a + Q_d \qquad \textbf{[B.a]}$$

where:

Q_L = heat lost from liner(s)

Q_s = heat entering from sun radiation

Q_a = heat taken out by ventilation

Q_d = heat losses through the R.C. windshield

Note: The effect of the sun may be calculated through a rather complicated system of equations based on heat transfer balances. Its influence depends upon the latitude, the time of day, the date, the orientation and the air composition (vapour, powders). The equations illustrating the phenomenon are, therefore, of the transient type.

The main effects are:

- Increase of the exposed surface temperature locally: Such increase may range from 5-8°C in sub-tropical zone or 20-25°C in tropical/desert zones.
- A positive gradient from the external shell temperature to the internal one (0-3°C in sub-tropical zones, 7-8°C in tropical/desert zones).

Nevertheless the impact on the temperature of the ventilation air even in tropical areas is limited to 2-3°C since the phenomenon is influencing only part of the chimney and the quantity of ventilation air is increased by the increase of the natural draught.

Finally the thermal gradients in the reinforced concrete shell are not increased significantly and the impact on the temperature of the ventilation air is limited also in tropical/ desert regions. Only in this last case the design of the ventilation system shall be taken into account, to allow for the inspection of the inner space. The air temperature calculated by neglecting the sun radiation can be actually 3-5°C more.

2.1.1. Unventilated air space

The equilibrium may be found through formula [B.a] with Q_a=0:

$$Q_L = K \cdot S \cdot (T - T_o) \qquad \textbf{[B.b]}$$

where:

K = overall heat transfer coefficient (W/m^2 K)
S = internal surface of all liners (m^2)
$T-T_o$ = temperature difference between average flue gas temperature and ambient air (°K)

and

$$\frac{1}{K} = \frac{1}{K_1} + \frac{t_b D_{bi}}{\lambda_b D_b} + \frac{t_i \cdot D_{bi}}{\lambda_i D_i} + \frac{D_{bi}}{K_s \cdot D_s} + \frac{t_c \cdot D_{bi}}{\lambda_c \cdot D_c} + \frac{D_{bi}}{K_2 \cdot D_{ce}} \qquad \textbf{[B.c]}$$

Coefficients are given in Appendix B1.

2.1.2 Ventilated air space

$$Q_L = K \cdot S \cdot (T - T_o) = Q_a + Q_d \qquad \textbf{[B.d]}$$

with the same meaning of symbols as in formula [B.b].

By defining:

$$Q_d = r_q \cdot Q_L$$
$$Q_a = (1 - r_q) \cdot Q_L$$

the formula [B.d] becomes:

$$K \cdot S \cdot (T - T_o) = (1 - r_q) Q_L + r_q \cdot Q_L \qquad \textbf{[B.e]}$$

since:

$$(1 - r_q) \cdot Q_L = c_p \cdot G \cdot (T_{ao} - T_o) \qquad \textbf{[B.f]}$$

where

$T_{ao} - T_o$ = rise in temperature of ventilation air

and

$$\frac{1}{K} = \frac{1}{K_1} + \frac{t_b \cdot D_{bi}}{\lambda_b \cdot D_b} + \frac{t_i \cdot D_{bi}}{\lambda_i \cdot D_i} + \left(\frac{D_{bi}}{K_r \cdot D_s} + \frac{t_c \cdot D_{bi}}{\lambda_c \cdot D_c} + \frac{D_{bi}}{K_2 \cdot D_{ce}} \right) \times r_q \qquad \textbf{[B.g]}$$

The equilibrium of the air space may be found by iteration through the above thermal balances and associated pressure equilibrium conditions.

Appendix B1 gives the values of coefficients.

Appendix B2 gives some suggestions to define this equilibrium.

Appendix B3 gives guidance for K_r and K_s in multiflue chimneys.

2.2 Steel chimneys

As specified under §1.2 the air space is usually unventilated. The approach is, therefore, according to §2.1.1 and the coefficients are given in Appendix B1.

Since a steel chimney is relatively low in height and has low mass, the effect of the heat from the sun is minor and normally neglected. Note that tall steel chimneys can deflect under the sun's heat and this can distort optical instrumentation.

APPENDICES TO SECTION B

B1 HEAT TRANSFER COEFFICIENTS

B1.1 Reinforced Concrete Chimneys

B1.1.1 Heat transfer coefficients from gas to the internal liner surface (K_1)

Suggested heat transfer coefficients are available from technical literature. The figures (Figure B1, from ACI 307) and formula hereunder have been inserted as a suggested approach. Common unit conversions to use are

°K = (°F - 32) x 5/9 +273

°F = (°K - 273) x 9/5 +32

feet = metres x 0.3048

1 BTU/ft^2-h °F = 5.67 W/m^2 °K

B1.1.2 Heat transfer between external liner surface and internal concrete surface for ventilated spaces

The overall coefficient is:

$$K_r = \frac{1}{\frac{1}{\alpha_c} + \frac{1}{\alpha_{irr}} + \frac{1}{\alpha_{c1}}}$$

where:

$$\alpha_c = 2 \cdot 2 \times \left(\sqrt[4]{T_{ie} - T_m} \right)$$

$$T_m = \left(T_o + T_{ao} \right) / 2$$

$$\alpha_{irr} = \frac{4.6}{T_{ie} - T_{ci}} \times \left[\left(\frac{T_{ie} + 273}{100} \right)^4 - \left(\frac{T_{ci} + 273}{100} \right)^4 \right]$$

$$\alpha_{ci} = 2 \cdot 2 \times \left(\sqrt[4]{T_m - T_{ci}} \right)$$

The contribution of the air conductivity may be neglected.

In case of sufficiently insulated liners the overall heat transfer coefficient ranges from 5-9 W/m^{2}K. Since in the formula [B.g] this term only slightly influences the total K, a reasonable and approximate value may usually be assumed in the above range.

B1.1.3 Heat transfer coefficient between external liner surface and internal concrete surface for unventilated spaces

As the air is assumed unmoving $\alpha_c = \alpha_{ci} = o$

thus $K_s = \alpha_{irr}$

B1.1.4 Heat transfer coefficient between outside chimney surface and the surrounding air (K_2)

The heat transfer from outside chimney surface to the surroundings is extremely influenced by the wind velocity and it may range from 7 to 70 W/m^{2}K.

The lowest K_2 value will be used for checking the suitability

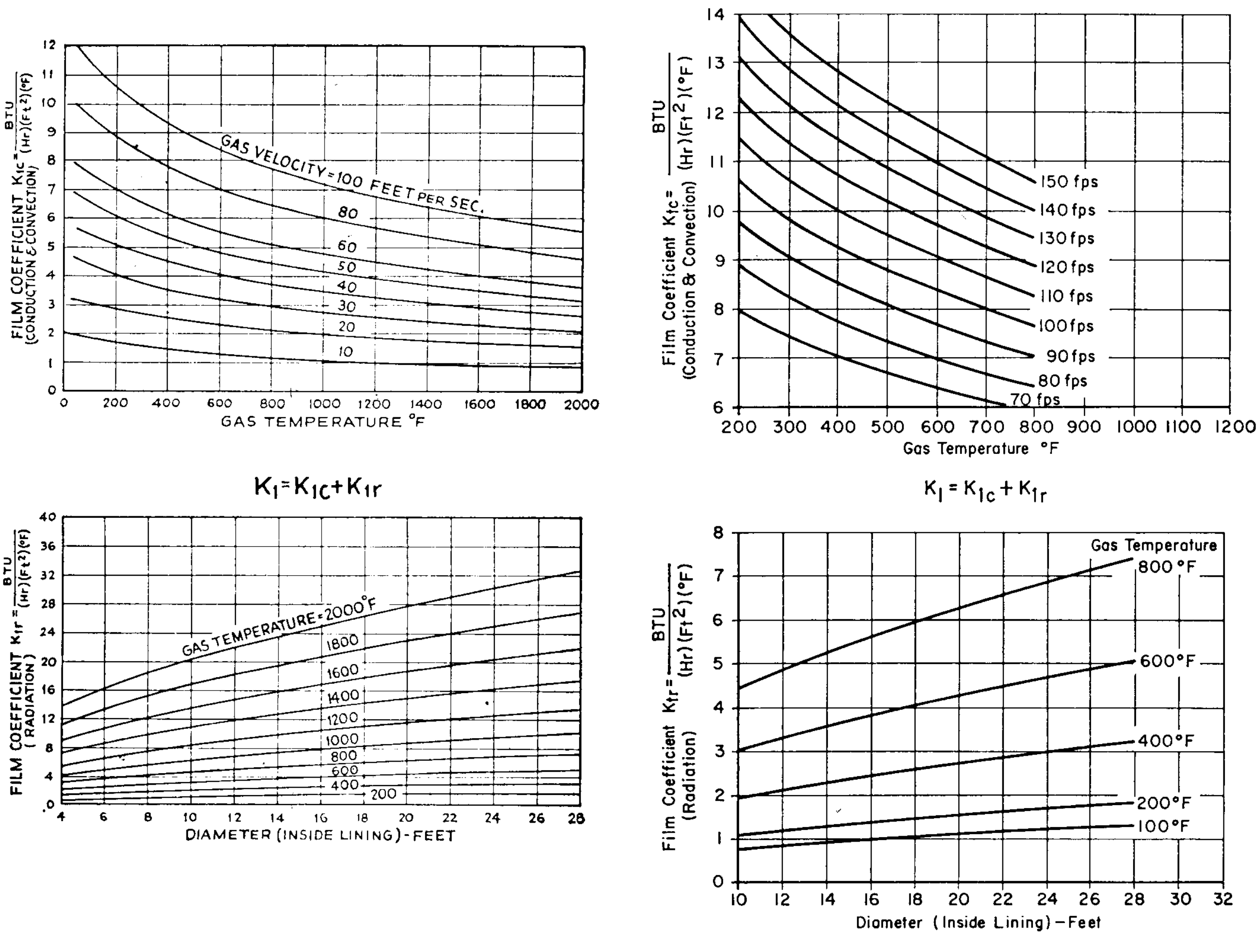


Figure B1—Flue gas film coefficients (from ACI 307)

of materials whereas the highest will be used to find the design thermal gradients.

B1.2 STEEL CHIMNEYS

Heat transfer coefficients for steel chimneys are presented in the following figures taken from ASME STS-1-1992. The figures are presented in Imperial units. The following conversion factors are presented for convenience.

1 °F = 9/5 °C + 32
1 ft = 0.3048m
1 inch = 0.0254m
1 mph = 1.609 km/h = 0.447 m/s
1 BTU = 0.252 kcal
1 BTU/hr-ft^2 = 4.88 kcal/h-m^2

B.2 SUGGESTED PROCEDURE FOR VENTILATED AIR SPACE CHIMNEYS

The value Q_L of formula [B.d] represents the heat lost by flue gases i.e.:

$$Q_L/S = C_g \times G_g \times (T_i - T_e) \qquad \textbf{[B2.a]}$$

where "i" and "e" are the temperatures at inlet/outlet. The formula may be transformed by using the average temp (T):

$$Q_L/S = 2 \times C_g \times G_g \times (T_i - T) \qquad \textbf{[B2.b]}$$

The heat lost by liner may be also expressed as follows:

$$Q_L / S = \frac{T - T_{ie}}{\frac{1}{K_1} + \frac{t_b \cdot D_{bi}}{\lambda_b \cdot D_b} + \frac{t_i \cdot D_{bi}}{\lambda_i \cdot D_i}} \qquad \textbf{[B2.c]}$$

By equating [B2.b] with [B2.c]:

$$2 \times C_g \times G_g \times (T_i - T) = \frac{T - T_{ie}}{\frac{1}{K_1} + \frac{t_b \cdot D_{bi}}{\lambda_b \cdot D_b} + \frac{t_i \cdot D_{bi}}{\lambda_i \cdot D_i}} \qquad \textbf{[B2.d]}$$

Thus, for fixed type and thickness of materials, there is a correlation between the average flue temperature (T) and the external temperature of insulation (T_{ie}). If the maximum flue temperature loss is fixed (due, for instance, to the dew point limit) or T_{ie} must be limited (safety aspect for the case of an inspectable air space) then one term defines the other.

The value of heat lost by the reinforced concrete windshield (see 2.1.2) may be expressed as:

$$r_q \cdot Q_L = \frac{\lambda_c}{t_c} \cdot (T_{ci} - T_{ce}) \times \frac{D_{bi}}{D_c} \qquad \textbf{[B2.e]}$$

where, if the maximum gradient in concrete is fixed, then the product $r_q \cdot Q_L$ is known.

Since Q_L and $r_q \cdot Q_L$ are known, then the heat to be brought out from ventilation air, $(1-r_q) \cdot Q_L$, is also known

At this stage it will be necessary to check if the existing ventilation can meet such values i.e. if the net draft in the ventilation space is in adequate for the required air quantity and the requested maximum ventilation air temperature By considering that:

$$(1-r_q) \cdot Q_L S = c_p \cdot G \cdot (T_{ao} - T_o) = 2 \cdot c_p \cdot G \cdot (T_a - T_o)$$

[B2.f]

where T_a = average ventilation air temperature.

Furthermore:

$$G = g_a \,.\, v_i \,.\, S_i$$ **[B2.g]**

where:

g_a, g_{in}	=	density of external air (kg/m ^{3})
g_{out}	=	density of ventilation air at outlet (kg/m ^{3})
v_{in}, v_{out}	=	velocity at inlet/outlet openings

and:

$$v_{in} = \sqrt{\frac{2 \cdot g \cdot (D - \Delta p) \cdot A}{\gamma_a \cdot \alpha_{in}}}$$

[B2.h]

$$v_{out} = \sqrt{\frac{2 \cdot g \cdot (D - \Delta p) \cdot (1 - A)}{\gamma_{out} \cdot \alpha_{out}}}$$ **[B2.i]**

where:

$(D - \Delta_p)$	=	net available draft
A	=	portion of $(D - \Delta_p)$ used in inlet openings
α_{in}, α_{out}	=	local coefficients [see below]

The term D will be calculated with formula [a] - sect A and Δ_p (pressure losses after the inlets) will be formed by friction losses (usually negligible due to the low air velocity) and local losses.

The local coefficients α may be suggested, for flush openings with sharp edges, as follows:

Reinforced concrete thk/hydraulic dia	
≥ 1.60	α = 1.50
1.60 - 0.90	α = 1.70
= 0.80	α = 1.85
= 0.40	α = 2.60

and the consequent pressure losses are:

$$\Delta p = \alpha \cdot \frac{v^2}{2g} \cdot \gamma$$

Notes:

- In chimneys with important variations in the size and thickness of components along its height, all variables should be evaluated section by section.
- In case of multiflue chimneys the geometrical liners surface, for what concerns the radiation, should be substituted by an "equivalent" radiating surface due to the mutual influence: see Appendix B3.

B3 EQUIVALENT DIAMETER FOR RADIATION LINER/ INNER CONCRETE SHELL IN MULTIFLUE CHIMNEYS

The radiation between liner(s) and inner concrete shell is governed by the Stefan-Boltzmann equation

$$Q = k \cdot S \cdot \left[\left(\frac{T_{ie}}{100}\right)^4 - \left(\frac{T_{ci}}{100}\right)^4\right]$$ **[B3.a]**

In the case of single flue chimneys, S is the external liner surface whereas - in case of multiflue chimneys - the total liners surface must be reduced to take into account re-radiation between portions of each liner as Fig. B3-1.

The actual radiating surface Se for each liner may be expressed as:

$$S_e = \pi \cdot D \left[1 \frac{(n-1)\,\alpha}{360}\right]$$

[B3.b]

and being:

$$\alpha_i = 2 \sin^{-1}\left(\frac{D/2}{d_i}\right)$$

The value of S_e and d_i may be obtained from the geometrical layout, as per Figure B3-1.

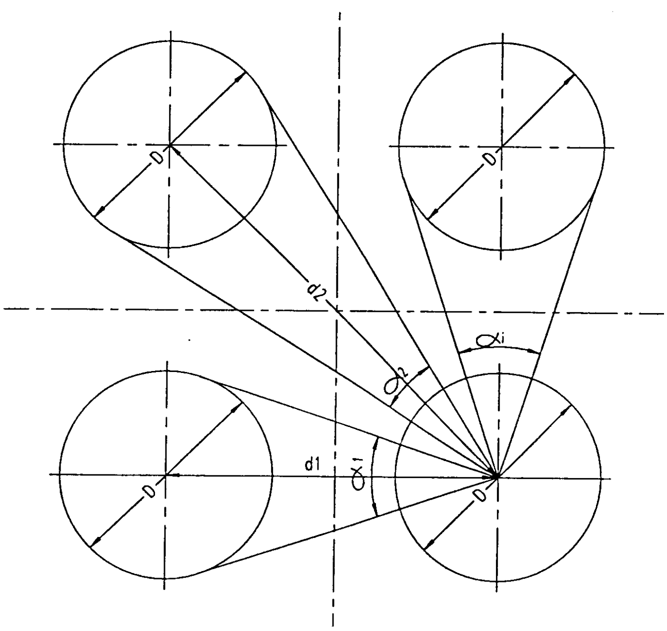


Figure B3-1

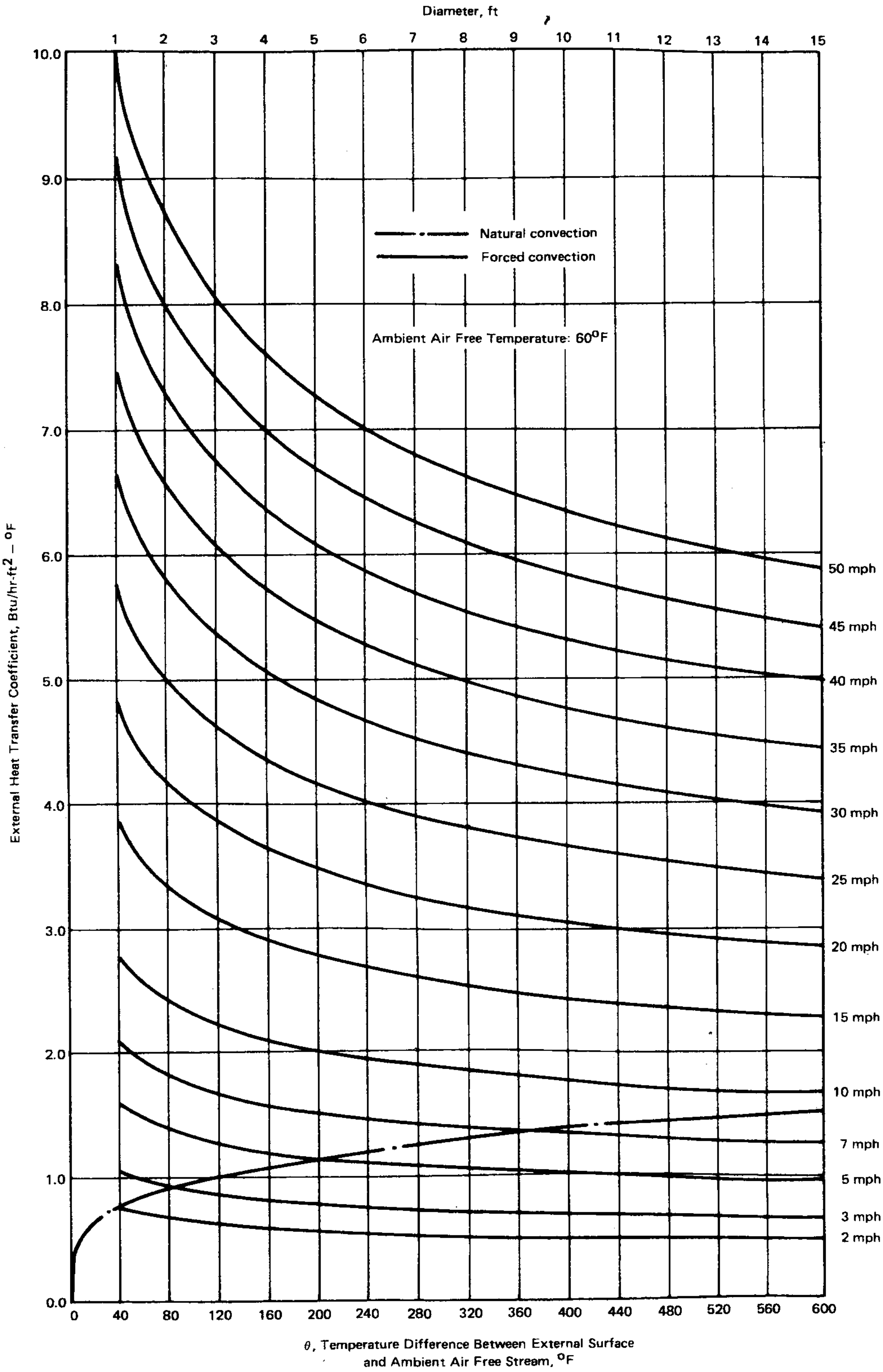
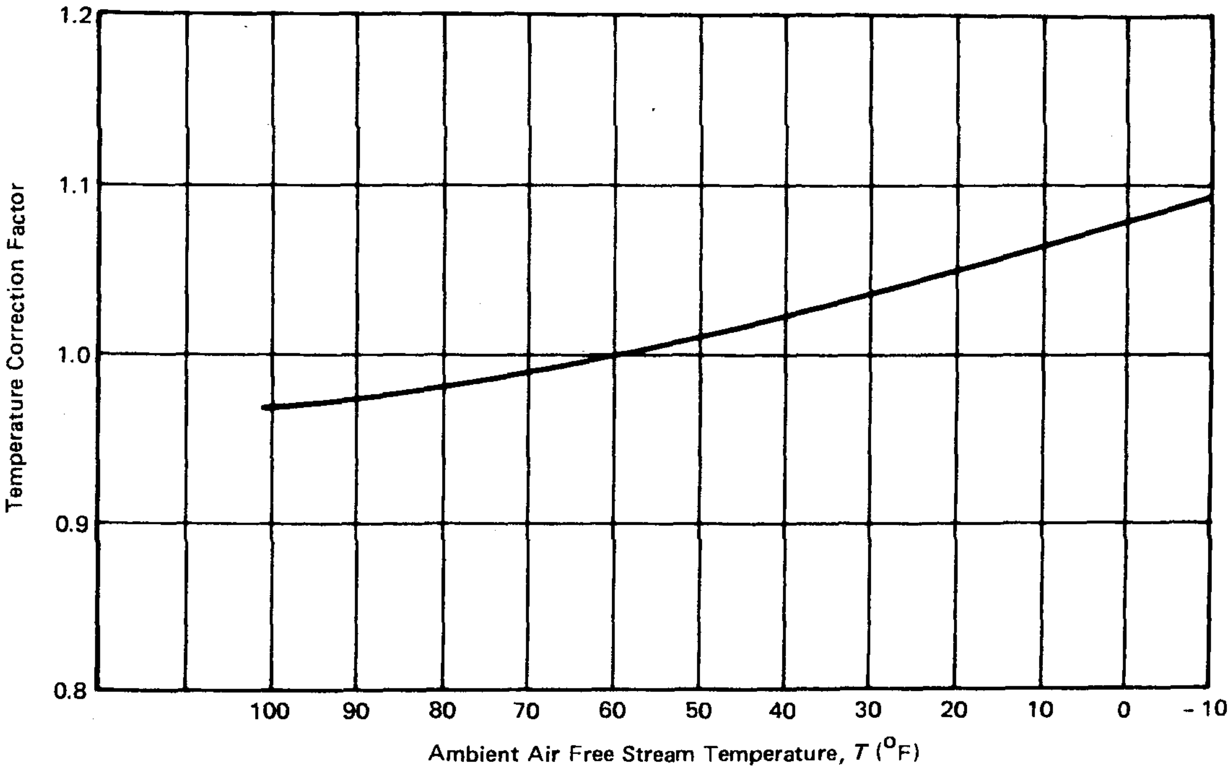


Figure B2-1 - External heat transfer coefficient for forced and natural convection
(courtesy of Warren Engineering, Inc.)



GENERAL NOTE
$h_T = (h_{60°F})$ (Temperature correction factor)$_T$ where h_T is the external heat transfer coefficient fro forced convection when the ambient air free stream temperature is T (°F); $h_{60°F}$ is the external heat transfer coefficient for forced convection for a T (°F) of 60°F (see Figure B2-1).

Figure B2-2 - Effect of change in the ambient air free stream temperature on the external heat transfer coefficient for forced convection
(courtesy of Warren Engineering, Inc.)

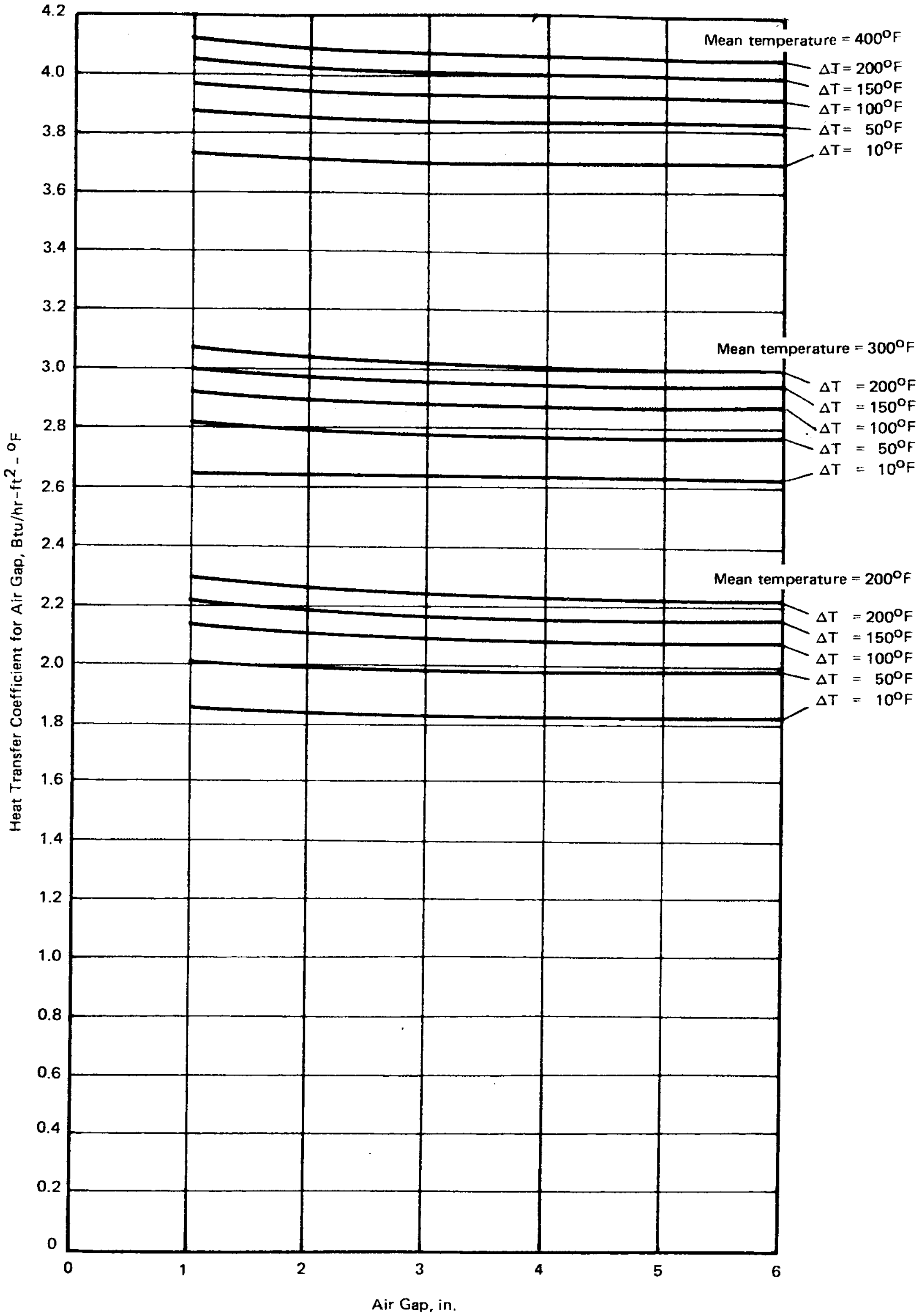


Figure B2-3 - Heat transfer coefficient for the air gap between two walls of a double-walled metal chimney
(courtesy of Warren Engineering, Inc.)

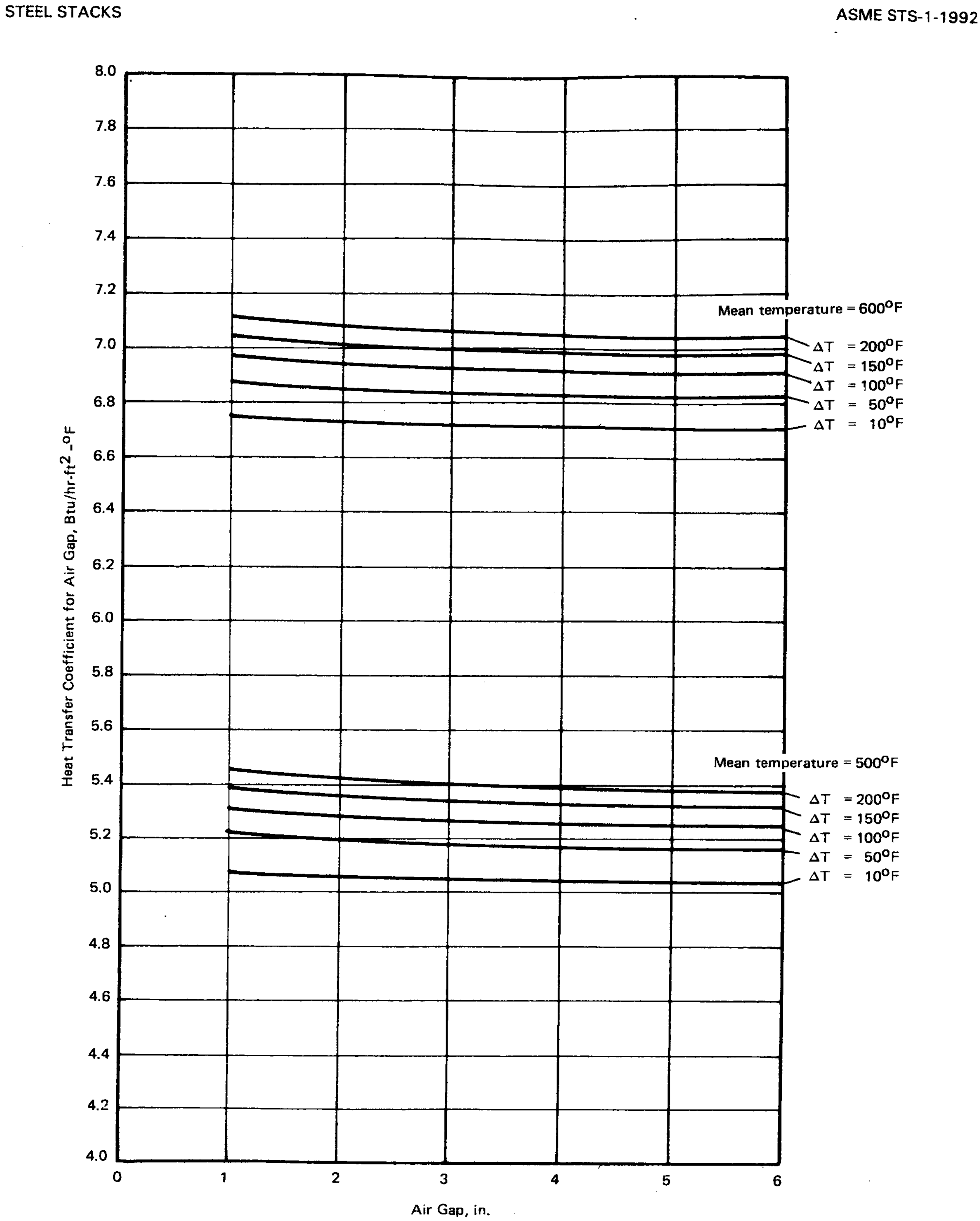


Figure B2-4 – Heat transfer coefficient for the air gap between two walls of a double-walled metal chimney

(courtesy of Warren Engineering, Inc.)

ASME STS-1-1992 STEEL STACKS

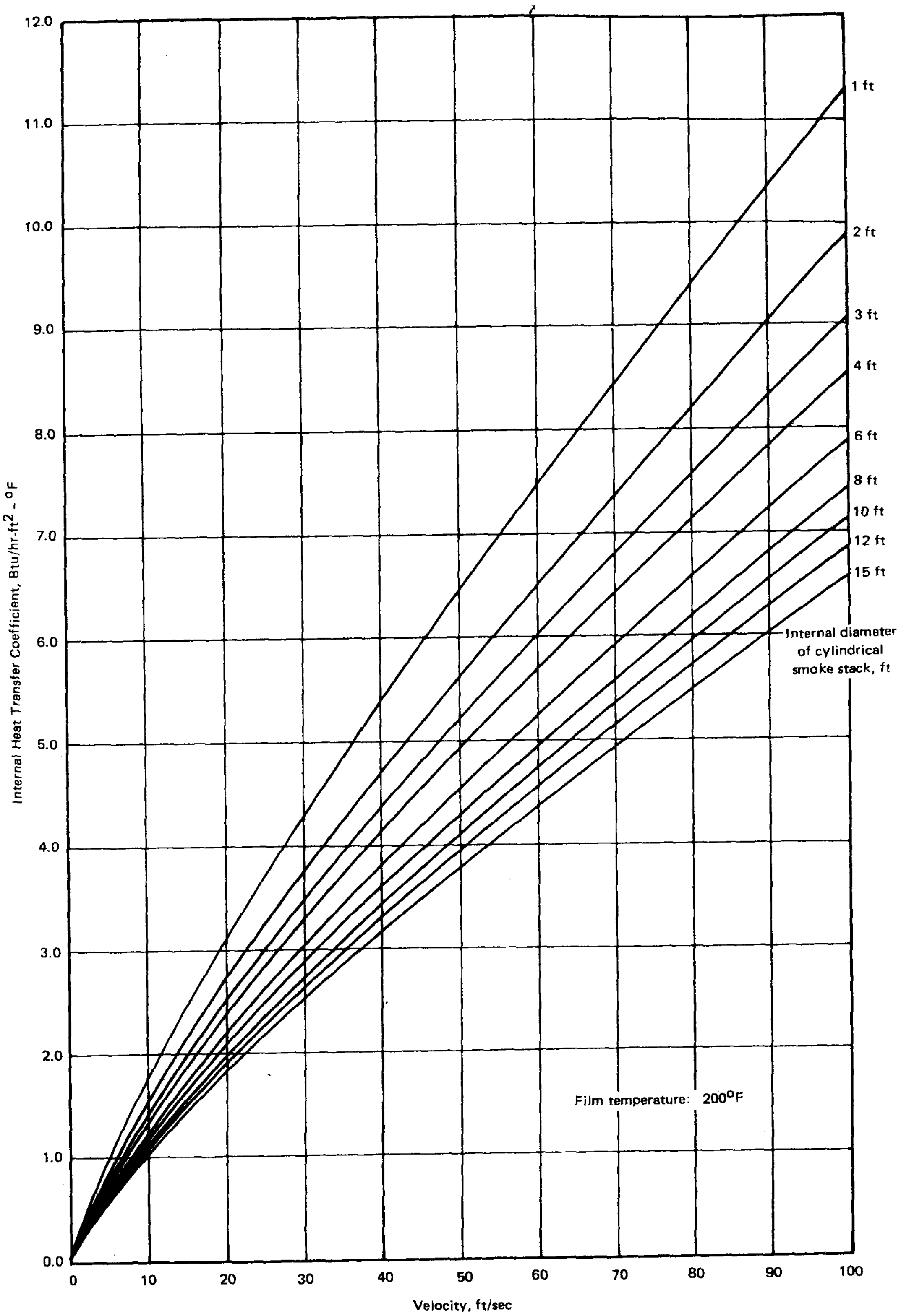


Figure B2-5 - Internal heat transfer coefficient (Btu/hr-ft^2-°F) vs. velocity (ft/sec) - film temperature of 200°F

(courtesy of Warren Engineering, Inc.)

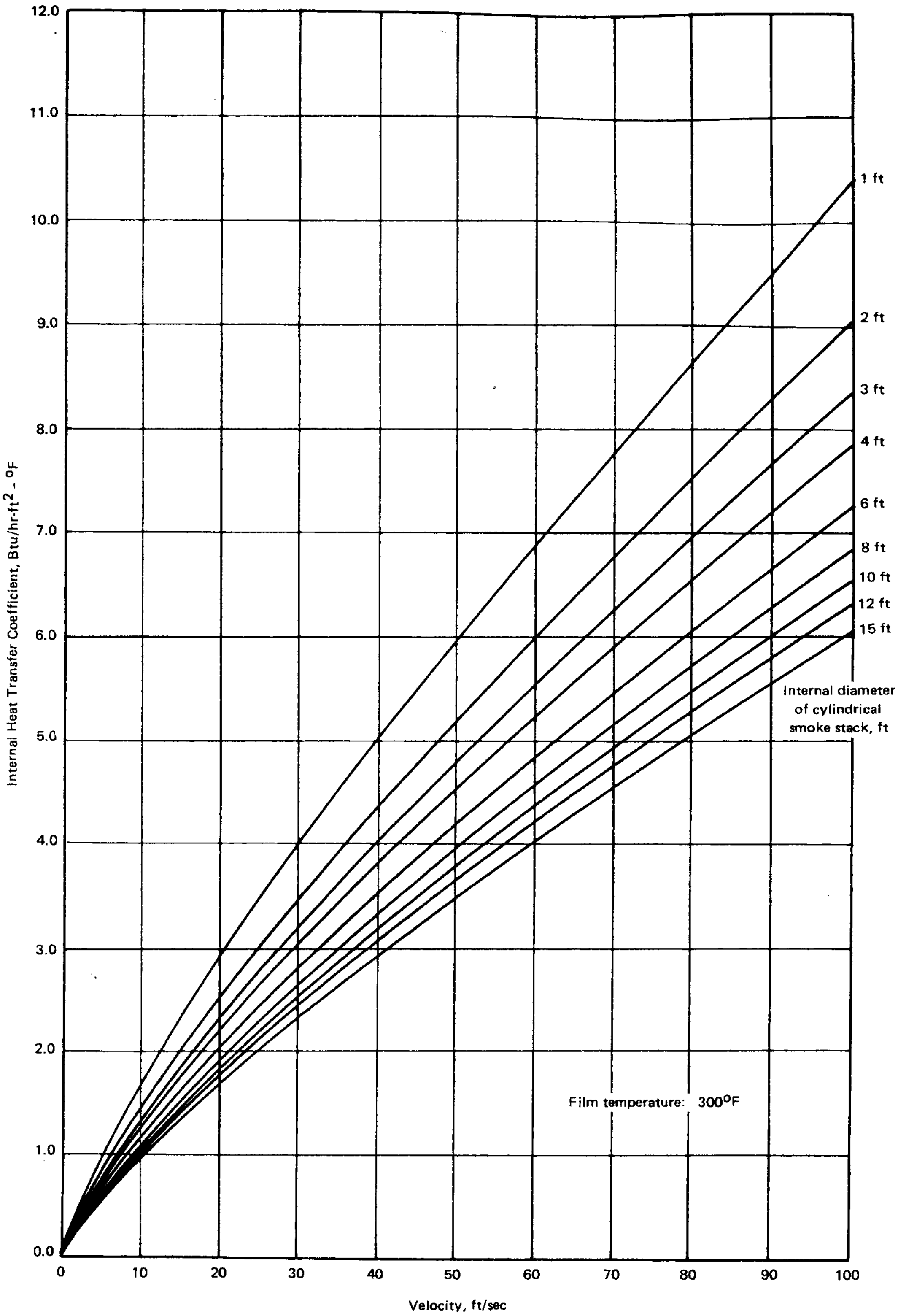


Figure B2-6 - Internal heat transfer coefficient (Btu/hr-ft^2-°F) vs. velocity (ft/sec) - film temperature of 300°F

(courtesy of Warren Engineering, Inc.)

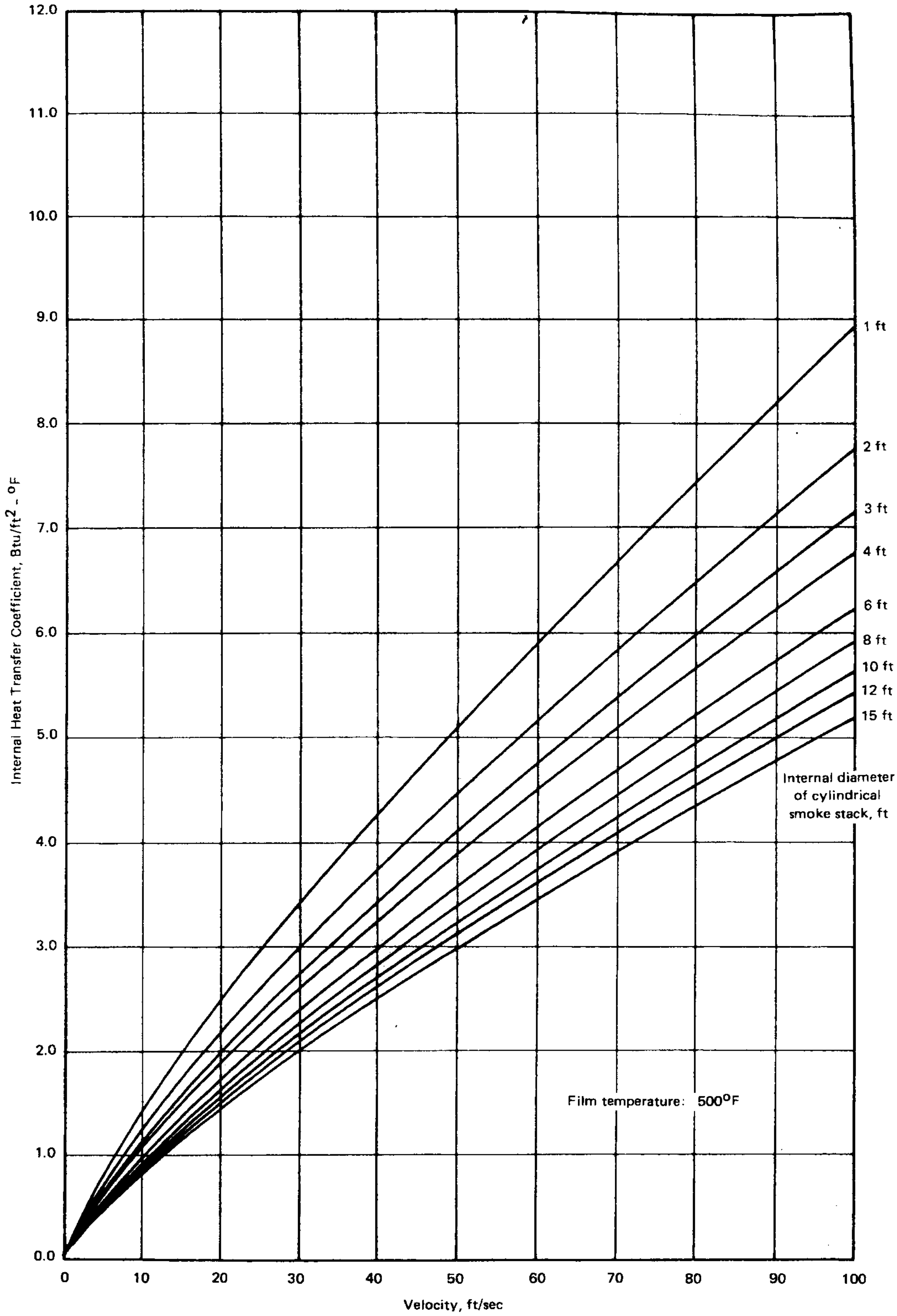


Figure B2-7 - Internal heat transfer coefficient (Btu/hr-ft^2-°F) vs. velocity (ft/sec) - film temperature of 500°F

(courtesy of Warren Engineering, Inc.)

STEEL STACKS ASME STS-1-1992

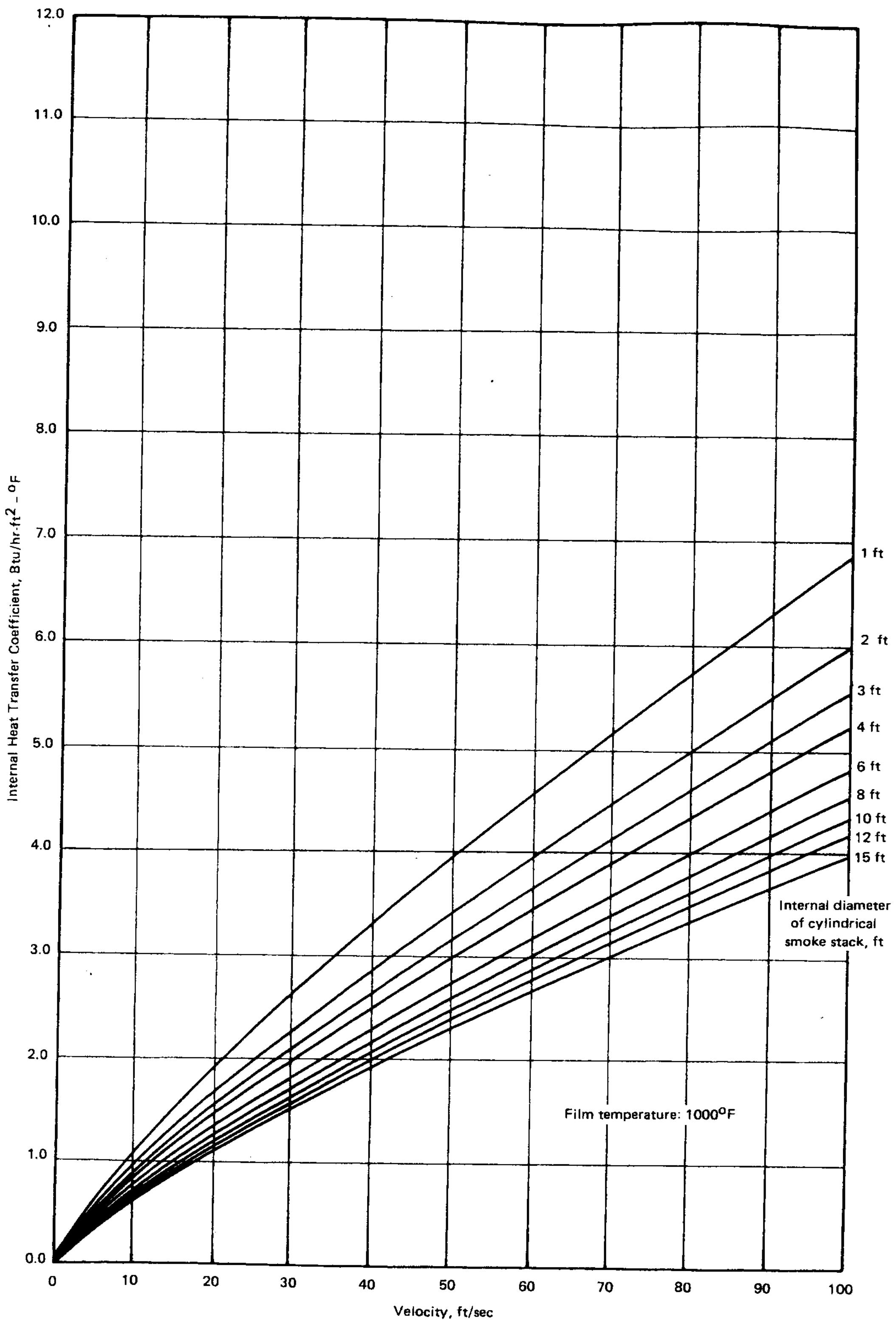


Figure B2-8 - Internal heat transfer coefficient (Btu/hr-ft^2-°F) vs. velocity (ft/sec) - film temperature of 1000°F

(courtesy of Warren Engineering, Inc.)

SECTION C

C1. PRESSURIZATION

With brick liners operating at low temperature it may happen that the flue gas pressure is higher than the ventilation air pressure. Such situations may cause leakage due to brick liner permeability, cracks and joints. Therefore, the pressurization of the inner space between liner(s) and the reinforced concrete windshield should be investigated.

It is suggested that two fans, one operating and one on stand-by, are installed to create a pressure of 25 - 50 mmH_2O above the flue gas pressure at chimney inlet.

C1.1 Calculation procedure

A procedure to determine the air requirement may be the following:

- calculate the air quantity on the basis of Appendix B2. Due to the limited flue gas temperature this quantity will be very low and, consequently, the pressure losses through the inner space will be negligible
- once the inner positive pressure P is fixed, the exit velocity of the ventilation air through any opening is given by:

$$v_i = \sqrt{\frac{\alpha \cdot 2g \cdot P}{\rho}} \qquad \textbf{[C.a]}$$

and the air quantity flowing through the opening surfaces S_i is given by:

$$G_p = \Sigma v_i s_i \qquad \textbf{[C.b]}$$

- compare the air quantity calculated with the procedure of Appendix B2 with equation [C. b]: the higher one - most probably from [C.b] - will determine the fan capacity
- careful attention should be paid to the difficulty of creating 100% efficient seals of openings such as inlet/outlet of liners, doors, aircraft warning light doors, etc.
- for α values see below.

For sectionally supported linings it will be necessary to seal the joints between sections to avoid air entrance in the liner.

Of course when there is a considerable air requirement and the velocity in the inner space or in particular zones (for instance restrictions created by intermediate slabs) is higher than about 2m/s, the pressure losses are no longer negligible. The pressure of the inner space will not be uniform so that formulae [C.a] and [C.b] will be applied section by section and an iterative procedure is required.

C1.2 Brickwork permeability

The calculation procedure of §1.2 does not take into account the brickwork permeability.

The quantity "Q" of air passing through a wall of thickness "s" and "S" surface under a pressure difference "Δp" is expressed as follows:

$$Q = \frac{\chi \cdot \Delta p \cdot S}{s} \qquad m^3/sec \qquad \textbf{[C.c]}$$

where:

χ = permeability

$$\left[\frac{m^3}{s}(\text{flow}) \times m(\text{brick thk}) \times \frac{1}{m^2(\text{brick lining surface})} \times \frac{1}{(\text{pressure difference})}\right]$$

Δp = pressure difference (mmH_2O)

S = brickliner surface area (m^2)

s = brickliner thickness (m)

The χ value depends upon the continuous porosity of the brickwork: suggested value is 2 - 3 x 10^{-6} $m^2/sec\ mmH_2O$

Note: The quantity of air calculated from [C.c] is - usually - very limited compared to the requirement of §C1.1, but conservative evaluation is suggested to take into account the presence of cracks in the brickliner.

C1.3 Fan pressure

Assuming that the system is perfectly tight so the total fan pressure is:

$$p_{tot} = p_{st} + p_{DYN} = p_{st} \qquad \textbf{[C.d]}$$

where:

p_{tot} = total pressure (mmH_2O)

p_{st} = static pressure (mmH_2O)

p_{DYN} = dynamic pressure (mmH_2O)

Since there is no air movement the fan should show: p_{st} = 25-50 mmH_2O (see §C1). Normally, however, air will be required for leakage in the system or for the need of exhausting heat lost from liners. Then the fan must supply all of the dynamic term i.e.:

$$\rho_{ex} \times \frac{v_{ex}^2}{2g} \qquad \textbf{[C.e]}$$

where:

v_{ex} = exit velocity from top windows (m/s)

ρ_{ex} = air density at exit temperature (kg/m^3)

The fan must supply the requested pressure (25-50 mmH_2O) plus the pressure losses along the ventilation air path, thus totalling:

$$p_{tot} = p_{st} + \alpha_{in} \cdot \frac{v_{in}^2}{2g}\rho_{in} + \alpha_{out} \cdot \frac{v_{ex}^2}{2g}\rho_{ex} + \Sigma\,\Delta p_{loc} + \frac{v_{ex}^2}{2g} \cdot \rho_{ex} \qquad \textbf{[C.f]}$$

where:

$\Sigma\,\Delta p_{loc}$ = local pressure losses from inlet to outlet windows and of the duct from fan

Coefficients α are specified under B.2 in Section B.

Particular attention should be paid to defining the top ventilation windows to limit pressure losses.

Formula [C.f] does not take the following into account:

- friction losses (almost always negligible)
- natural draft created by the difference in temperature

between external air and ventilation air since such a difference is very limited.

C2. DEW POINT

The temperature of acid dew point of gas containing water vapour and sulphur trioxide can be taken from Fig. C1, which shows the most common cases.

When the SO_3 content is unknown, a 5% (conservative) conversion of SO_2 into SO_3 may be assumed.

Since chemical effects are already commented on in CICIND's Model Code for Concrete Chimneys, Para. 6.4 of "Part B: Brickwork linings" and Para. 7.8 of "Part C: Steel liners", no further remarks will be given here.

However, it should be taken into account that particular chimney areas may be below the dew point even if the flue gas is above it, due to local cooling from:

- protruding parts (flanges, stiffeners, supports) etc., if not sufficiently insulated
- air leakage
- supporting/guiding points
- down draught at the chimney top.

C3. THERMAL EXPANSION

The coefficients of thermal expansion for materials normally used in chimneys are listed in Table C1.

These coefficients shall be used in connection with the maximum operating temperature (or with the long term abnormal maximum temperature, if any) to calculate the vertical and horizontal expansion of liner materials, with the following purposes:

- to avoid contact between independent liner sections
- to avoid contact with adjacent supports
- to define the correct height of the expansion joints
- to correctly size the top rain hood
- to take into due account differential expansion between chimney components.

Referring to the last sentence, particular attention shall be paid in designing liner sections with multiple openings in the presence of partition walls (though see A3.2.1.2).

The sun effects on the external reinforced concrete windshield and steel chimneys are covered by the relevant CICIND Model Codes.

C4. MONITORING AND INSTRUMENTATION

If required, chimneys shall be designed to incorporate appropriate facilities for the installation of instruments, continuous or intermittent, and environmental monitoring. Monitoring may include:

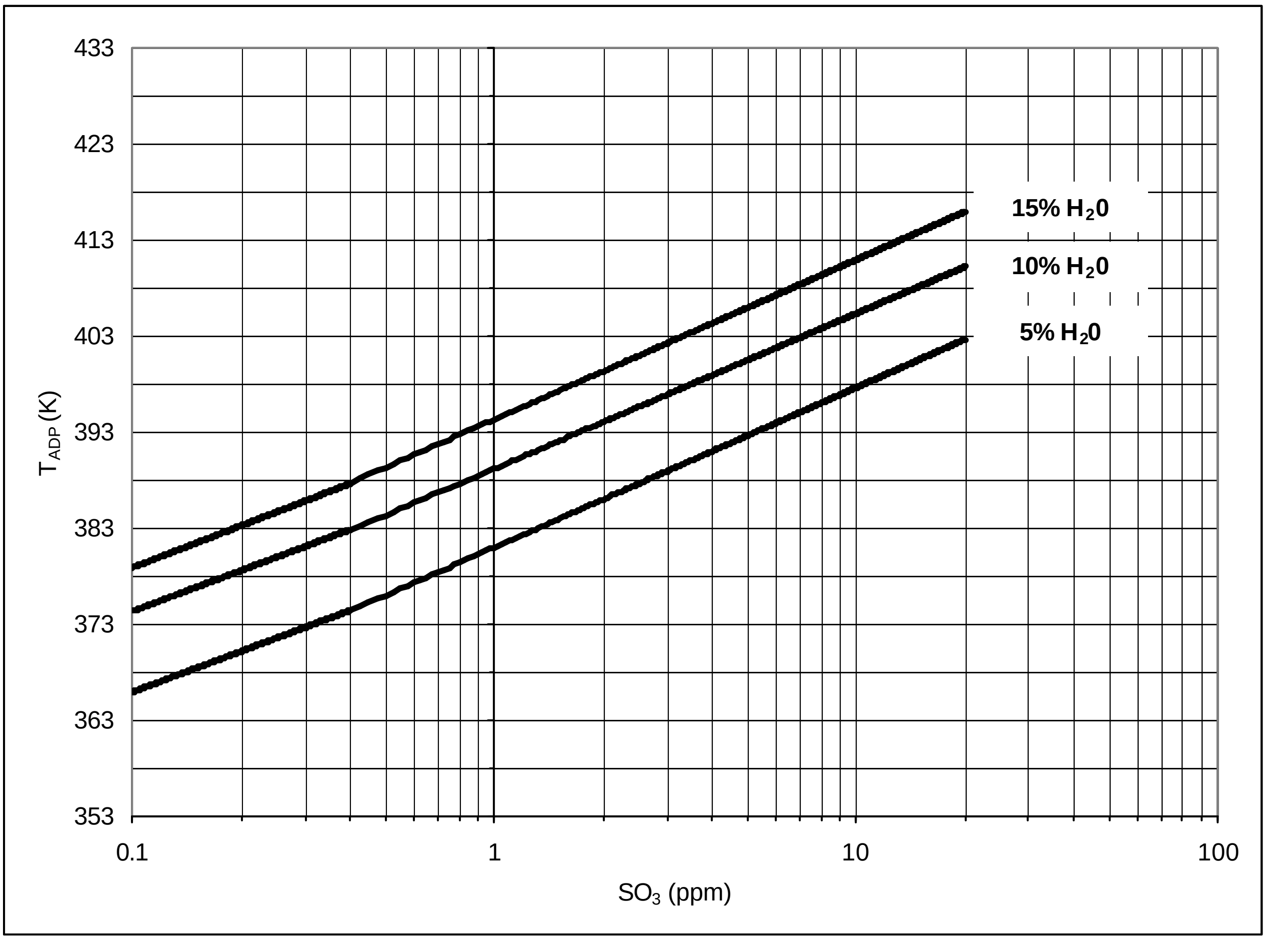


Figure C1 - Temperature of the acid dew point, T_{DP}, of gases containing water vapour (H_2O) and sulphur trioxide (SO_3)

- pressure conditions,
- gas flow velocity,
- gas flow temperature,
- oxygen,
- carbon dioxide,
- nitrogen oxides,
- sulphur oxides,
- particulates,
- other gases.

Platforms with sufficient clearance for access to equipment and for personnel should be constructed. These platforms should be located at a chimney height within the range of five times the flue diameter from the flue gas entrance section and three times the diameter from the outlet of the chimney, or as required by local regulations. The platforms should have a clear and easy vertical access, whenever possible through staircase or elevator.

Instrumentation platforms should be equipped with electrical power and lighting. Compressed air, material hoist, safety equipment or telephone would be useful.

Provision should be made for test ports with sealed and covered openings to permit the installation of instrumentation. When continuous monitoring is required, appropriate devices should be provided to allow transmission of the information to the control centre.

Material	$°C^{-1}$
Brickwork	$6\text{-}7 \times 10^{-6}$
Carbon steel and ASTM A-242	1.2×10^{-5}
Stainless steel	1.8×10^{-5}
Ni super alloys (ASTM B-575)	1.25×10^{-5}
Titanium	0.9×10^{-5}
Glass reinforced plastic	$7\text{-}9 \times 10^{-6}$
Reinforced concrete	10^{-5}

Table C1 - Coefficients of thermal expansion