Formulário 2018/19 Sistemas Energéticos em Edifícios

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Constante de Stefan-Boltzmann: $\sigma = 5.67 \times 10^{-8}\ W \cdot m^{-2} K^{-4}$

Heat Transfer

Thermal resistance

Thermal resistance: $R = \dfrac{L}{kA}$

Resistances in serie: $R_{eq} = \sum_{i=1}^{n} R_n$

Resistances in parallel: $R_{eq} = \left(\sum_{i=1}^{n} R_n^{-1} \right)^{-1}$

U-value and Psi-value

$$U = \frac{1}{R_{eq} A}$$

$$\Psi = \frac{q * / \Delta\theta - U_x A_x - U_y A_y}{B}$$

Heat conductance: H=UA

Surface-to-air heat transfer

Fundamentals

Nusselt number: $\text{Nu} = \dfrac{hL}{k_f}$

Prandtl number: $\text{Pr} = \dfrac{\nu}{\alpha}$

Rayleigh number: $\text{Ra}_L = \dfrac{g\beta(T - T_\infty)L^3}{\nu\alpha}$

Grashof number: $\text{Gr}_L = \dfrac{g\beta(T - T_\infty)L^3}{\nu^2}$

Reynolds number: $\text{Re}_L = \dfrac{\rho U_\infty L}{\nu}$

Vertical Walls

$$\text{Nu}_L = 0.59 \text{Ra}_L^{1/4} \quad 10^4 \leq \text{Ra}_L \leq 10^9 (laminar)$$

$$\text{Nu}_L = 0.1 \text{Ra}_L^{1/3} \quad 10^9 \leq \text{Ra}_L \leq 10^{13} (turbulent)$$

Horizontal Walls

Upwards heat flow:

$\text{Nu}_L = 0.54 \text{Ra}_L^{1/4} \quad 10^4 \lesssim \text{Ra}_L \lesssim 10^7$, $\text{Pr} \gtrsim 0.7$

$\text{Nu}_L = 0.15 \text{Ra}_L^{1/3} \quad 10^7 \lesssim \text{Ra}_L \lesssim 10^{11}$, toda a gama de Pr

Downwards heat flow:

$$\text{Nu}_L = 0.27 \text{Ra}_L^{1/4} \quad 10^5 \lesssim \text{Ra}_L \lesssim 10^{10}$$

Surface film resistance [m^{2}K/W]

$R''_s = \dfrac{1}{h_c + h_r} = \dfrac{1}{h_s}$

External environment: $R''_{se} = 0.04$

Internal, horizontal heat flow: $R''_{si} = 0.13$

Internal, vertical upwards heat flow: $R''_{si} = 0.10$

Internal, vertical downwards heat flow: $R''_{si} = 0.17$

Surface-to-surface heat transfer

Air cavities

(print slides pp. 24 and 25 SEE-Radiation)

Network analysis

Ventilation

Heat flow: $q = \dot{m}\, c\, \theta = \rho\, c\, \dot{v}\, \theta$

Conductance: $H_v = \rho\, c\, \dot{v} \simeq 1200\, \dot{v}$

Simplification rules

Multiple conductances connected to different temperature nodes: $H_{eq} = H_1 + H_2 + ... + H_n$

$$\theta_{eq} = \frac{\theta_1 H_1 + \theta_2 H_2 + ... + \theta_n H_n}{H_1 + H_2 + ... + H_n}$$

Heat flow (q_0) with a conductance (H_0) connected to a temperature node (θ_0): $H_{eq} = H_0$

$$\theta_{eq} = \theta_0 + \frac{q_0}{H_0}$$

Radiative heat transfer

$q_i = A_i \varepsilon^* h_r^* (T_i - T_j)$

$h_r^* = 4\sigma \overline{T}_{ij}^3$

Enclosure with two surfaces

$$\varepsilon^* = \left(\frac{1 - \varepsilon_i}{\varepsilon_i} + \frac{1}{F_{ij}} + \frac{1 - \varepsilon_j}{\varepsilon_j} \frac{A_i}{A_j} \right)^{-1}$$

Enclosure with two parallel surfaces

$$\varepsilon^* = \left(\frac{1}{\varepsilon_i} + \frac{1}{\varepsilon_j} - 1 \right)^{-1}$$

Solar geometry

$\alpha = \arcsin(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta)$
$\varphi = \arccos\left(\frac{\sin\alpha\sin\phi - \sin\delta}{\cos\alpha\cos\phi}\right)$
$\delta = 0.4093\sin\left(2\pi\frac{284+J}{365}\right)$ [rad]
$\omega = 0.2618(h-12)$ [rad]
$\vartheta = \arccos(\cos\alpha\cos\gamma\sin\beta + \sin\alpha\cos\beta)$

ϑ - incidence angle of solar radiation on a β sloped surface (angle between the sloped surface the horizontal plane)
α - solar altitude
γ - azimuth difference between the sun (φ) and the surface (ψ)
ϕ - latitude
δ - solar declination
ω - angular solar hour
J - Julian day

Solar gains

g-value

Glazing-to-internal node conductance: H_{ji}
Glazing-to-external node conductance: H_{je}

Simple glazing: $g = \tau + \alpha\frac{H_{ji}}{H_{ji}+H_{je}}$

Angular correction: $g(\vartheta) = F_w g_\perp$

Frame correction or glazing factor: $F_g = \frac{A_g}{A_w}$

Obstruction factors: F_o, F_f and F_h

Solar gains

Transparent (no shading elements)

$A_{sol} = F_w g_\perp F_g A_w$

Opaque

$A_{sol} = \alpha R''_{se} U A_{op}$

Energy balance

$q_{in} + q_{int} = q_{out}$ [W]

Steady-state

Steady-state:
$Q_{in} + Q_{int} = Q_{out}$ [J or Wh]
Auxiliary systems (thermostatic):
$Q_{aux} = Q_{out} - (Q_{in} + Q_{int})$ [J or Wh]

Quasi-steady-state

Heating needs:
$Q_{nd,H} = Q_{ht} - \eta_g Q_{gn}$ [J or Wh]

Cooling needs:
$Q_{nd,C} = (1-\eta_g)Q_{gn}$ [J or Wh]
Utilisation gain factor:

$\gamma = \frac{Q_{gn}}{Q_{ht}}$
$\eta_g = \frac{1-\gamma^a}{1-\gamma^{a+1}}$

For $\gamma = 0$, $\eta_g = \frac{a}{a+1}$

For $\gamma < 0$, $\eta_g = 1/\gamma$

Heat transfer:
$Q_{ht} = (H_{tr} + H_{ve})L(\theta_{set} - \overline{\theta}_{ext}) = (H_{tr} + H_{ve})\; GD_{\theta_{set}} \times 24$

$H_{tr} = H_d + H_g + H_u + H_a$

$H_x = b_{tr,x}(\sum A_i U_i + \sum B_i \Psi_i)$

$H_{ve} = \rho_a c_a \sum_k b_{ve,k}\phi_{ve,k}$

Adjust factor: $b_{tr} = \frac{\theta_i - \theta_u}{\theta_i - \theta_e}$

Heat gains: $Q_{gn} = Q_{sol} + Q_{int} - \Delta Q_{sky}$

$Q = \Phi L$, with Φ the average power

$\Phi_{sol} = \sum_j \Phi_{sol,j}$

$\Phi_{sol,j} = G_j \sum_n F_{sh,n} A_{sol,n}$

Effective collecting area for opaque elements
$A_{sol,n} = \alpha_n R_{se} U_n A_n$

Effective collecting area for transparent elements
$A_{sol,n} = \overline{g}_{\theta,n} F_g A_{w,n}$

$\overline{g}_\theta = \overline{g}_{sh,\theta}\; F_{ms} + \overline{g}_{g,\theta}(1 - F_{ms})$

Shading elements: $\overline{g}_{sh,\theta} \simeq \overline{g}_{sh,\perp}$

Only glazing: $\overline{g}_{g,\theta} = F_w\; \overline{g}_{g,\perp}$

Alternative formulation for solar gains: $Q_{sol} = \sum_j E_j \left(\sum_n F_{sh,n} A_{sol,n}\right)_j$
Sky radiative exchanges: $\Delta Q_{sky} = h_r F_{sky} \Delta\theta_{sky} A_s$

Psicrometry

Humidity ratio: $W = \frac{m_v}{m_a}$

Relative humidity: $\phi = \frac{x_v}{x_s}$

Degree of saturation: $\mu = \frac{W}{W_s}$

Enthalpy of moist air: $h = h_a + Wh_v$ [J/kg$_a$]

$h = c_{pa}\theta + W(h_{fg} + c_{pv}\theta) \simeq 1.0\theta + W(2500 + 1.86\theta)$ [kJ/kg$_a$]

Pressure: $P = p_a + p_v$

$$\phi = \frac{p_v}{p_s} = \frac{\rho_v}{\rho_s}$$

$$\phi = \frac{W}{0.62198}\frac{p_a}{p_s}$$

$$W = 0.62198\frac{p_v}{1 - p_v}$$

Heating moist air or cooling with no condensation

Energy balance: $\dot{m}_a h_1 + q = \dot{m}_a h_2$
Water mass flow balance: $\dot{m}_a W_1 = \dot{m}_a W_2$
(Note: for cooling q is negative.)

Cooling and dehumidifying of moist air

Energy balance: $\dot{m}_a h_1 + q = \dot{m}_a h_2 + \dot{m}_w h_w$
Water mass flow balance: $\dot{m}_a W_1 = \dot{m}_a W_2 + \dot{m}_w$
(Note: for cooling q is negative.)

Heating and humidifying moist air

Energy balance: $\dot{m}_a h_1 + q + \dot{m}_w h_w = \dot{m}_a h_2$
Water mass flow balance: $\dot{m}_a W_1 + \dot{m}_w = \dot{m}_a W_2$

Adiabatic humidification of moist air

Energy balance: $\dot{m}_a h_1 + \dot{m}_w h_w = \dot{m}_a h_2$
Water mass flow balance: $\dot{m}_a W_1 + \dot{m}_w = \dot{m}_a W_2$

Adiabatic mixing of two streams of moist air

Energy balance: $\dot{m}_{a1} h_1 + \dot{m}_{a2} h_2 = \dot{m}_{a3} h_3$
Water mass flow balance: $\dot{m}_{a1} W_1 + \dot{m}_{a2} W_2 = \dot{m}_{a3} W_3$

Interstitial condensation

Mass flow rate of vapour: $\dot{m}_v'' = \frac{p_{v1} - p_{v2}}{R_v} = \frac{p_{v1} - p_{v2}}{r_v L}$

Thermal comfort

Operative temperature: $T_{op} = aT_a + (1-a)T_r$
$a = 0.5 + 0.25v_a$

Ventilation

Steady-state

$$\dot{V} = \frac{P}{C_i - C_o}$$

(Note that C_i and C_e are expressed in ppm $\times 10^{-6}$)

$$\dot{V} = \frac{P}{W_i - W_o}$$

Transient

$$V\frac{dC_i}{dt} = C_o\dot{V} + P - C_i(t)\dot{V}$$
$$C_i(t) = C_e + \frac{P}{\dot{V}}\left[1 - \exp\left(-\frac{\dot{V}}{V}\,t\right)\right]$$

Load calculation

Winter conditions

$T_o < T_i$
$$\rho_a c_{pa} V_{room}\frac{dT_i}{dt} = q_{heat,s} - q_{vent} - \sum_n A_n U_n (T_i - T_o)$$
$$q_{vent} = \rho_a c_{pa}\dot{V}(T_i - T_o)$$

Summer conditions

$T_o > T_i$
Sensible load

$$\rho_a c_{pa} V_{room}\frac{dT_i}{dt} = q_{cool,s} + q_{int} + q_{sol} + q_{vent} + \sum_n A_n U_n (T_o - T_i)$$
$$q_{vent} = \rho_a c_{pa}\dot{V}(T_o - T_i)$$

Latent load
$\dot{m}_a W_i = \dot{m}_a W_e + \dot{m}_w$
If $W_i > W_{max}$, $q_{cool,l} = \dot{m}_a (W_i - W_{max})\, h_{fg}$