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Re-creating Hottel's emissivity charts for water vapor and extending them to 40 bar pressure using HITEMP-2010 data base

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ABSTRACT

Hottel's water vapor emissivity chart and the pressure correction chart have been re-created using the most recent HITEMP-2010 data base to provide more accurate values. Hottel's standard emissivity has been redefined in order to produce smooth and accurate graphs and correlations. The new charts allow for calculating the water vapor emissivities at homogeneous pathways up to 200 bar equivalent pressure, in the 450–3000 K temperature range and in the 0.01–3000 bar cm pressure path length range; a departure from the original Hottel's emissivity values can be larger than 300% at high pressures. Departures from Leckner's (1972) correlations are typically in the ±40% range. Besides the new paper graphs, showing the standard emissivity as well as the pressure correction factor at different temperatures, the calculated emissivities have been tabulated (see Supplementary material) at equivalent pressures ranging from 0.05 bar up to 250 bar. Using appropriate interpolation techniques, these charts can be used as look-up tables to calculate accurate total emissivity values without using pressure correction factors. To this end, linear interpolation for temperature scaling and logarithmic interpolation for pressure and pressure path length scaling are included in the Supplementary material.

1. Introduction and objectives

In our preceding work [1] we have re-calculated both, the carbon dioxide standard emissivity chart and the pressure correction chart which have been originally proposed by Hottel and his co-workers, e. g. see Ref. [2]. For the re-creation of these charts the line-by-line model was used in conjunction with the most recent HITEMP-2010 [3] spectral data base. At elevated pressures, the standard Lorentz lineshape was modified using a simple line-cutoff criterion to compensate for the imperfection of this lineshape. Recently, we compared the HITEMP-2010 calculated spectral as well as total (integrated) emissivities with measured spectra [4] and found HITEMP-2010 to be an excellent data base for the calculation of absorption coefficients and/or emissivities of carbon dioxide and water vapor as well as their mixtures at atmospheric pressures.

The objective of this paper is to re-create two other Hottel's charts: the principal graph for water vapor, shown in Fig. 1, and the pressure correction chart, shown in Fig. 2. Both graphs are recommended in many engineering textbooks [5–8] and indeed, these are original Hottel's graphs developed around 60 years ago [2,9,10]. In this paper we review Hottel's work and explain how these charts (Figs. 1 and 2) have been developed. We further discuss Leckner's and Farag's works to improve these charts. In Section 3 we describe the method which is used to produce the new charts. Finally, we present our newly developed charts in Section 4.

2. Hottel's, Leckner's and Farag's work concerning water vapor

2.1. Standard and total emissivity of gases[1]

Generally, spectral emissivity $\varepsilon_{\eta,\,i}$ of an absorbing gas "i" in a mixture with other (remaining) gases "r_j" depends on temperature T, total pressure P_t, partial pressure of the absorbing gas p_i, partial pressures of the remaining gases p_r, and the pressure path length $p_i \cdot L$. Thus, spectral emissivity can be written as

$$\varepsilon_{\eta,i}(\eta, T, P_t, p_i, p_r, p_i \cdot L) = 1 - \exp\left(-K^p_{a,\eta} \cdot p_i \cdot L\right) \qquad (1)$$

where η represents the wavenumber while L is the path length; $K^p_{a,\eta}$ is the spectral absorption coefficient based on pressure. The concept of standard emissivity of gas "i" (ε^0_i) is to replace the self-broadening effect with the foreign broadening so that the influence of collisions between own molecules is neglected and p_i in

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[1] See Section 2.1 in Ref. [11] or Section 2.1 in Ref. [1]

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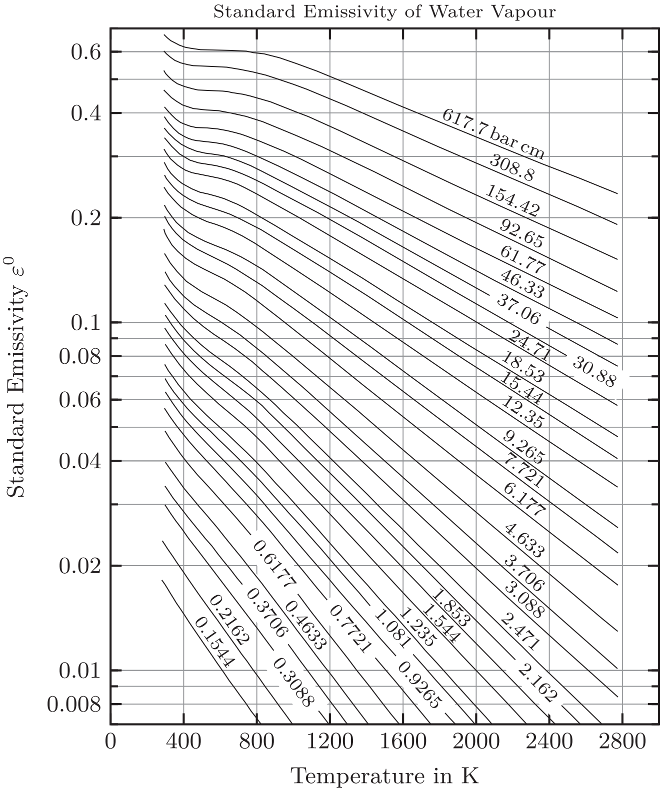

Fig. 1. Hottel's principal chart for water vapor, reproduced from Hottel and Sarofim [2] and converted to SI units.

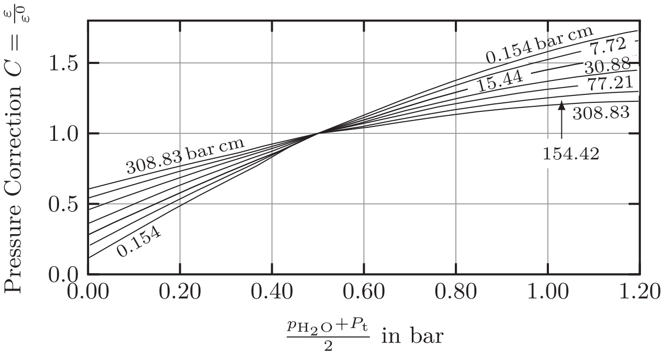

Fig. 2. Hottel's first pressure correction chart, reproduced from Hottel and Sarofim [2] and converted to SI units.

Eq. (1) appears only once, so

$$\varepsilon_i^0(T, p_r, p_i \cdot L) = \frac{\int_0^\infty \varepsilon_{\eta,i}(\eta, T, P_t = 1\,\text{atm}, p_i = 0, p_r, p_i \cdot L) \cdot \dot{e}_{\eta,b}(\eta, T) \cdot d\eta}{\sigma \cdot T^4} \qquad (2)$$

Superscript 0 indicates that the standard emissivity is calculated at standard total pressure $P_t = 1\,\text{atm} = p_r$ and $p_i = 0\,\text{atm}$. In the above expression, $\dot{e}_{\eta,b}(\eta, T)$ stands for the blackbody emissive power. Since $p_r = P_t$, standard emissivity ε_i^0 is now a function of two variables; temperature T and path length $p_i \cdot L$. One can define a pressure correction factor C accounting for the ratio of the total and the standard emissivities. This becomes

$$C(P_t, T, p_i, p_r, p_i \cdot L) = \frac{\varepsilon_i(T, P_t, p_i, p_r, p_i \cdot L)}{\varepsilon_i^0(T, P_t = 1\,\text{atm}, p_r, p_i \cdot L)} \qquad (3)$$

The concept of the standard emissivity and the pressure correction was introduced for the first time by Hottel and Egbert [9] in conjunction with their work on water vapor.

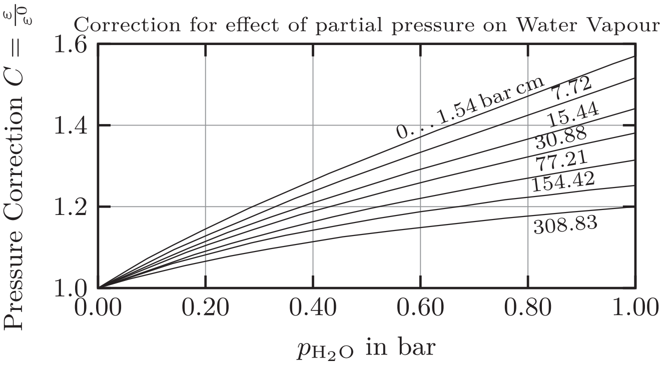

Fig. 3. Hottel's chart for converting total emissivity into standard emissivity, reproduced from Hottel and Egbert [9] and converted to SI units.

2.2. Measured data and the H_2O emissivity charts

The first attempt of producing the H_2O emissivity chart was made in 1935 by Hottel and Mangelsdorf [12]. In their chart, measured total emissivities at different pressure path lengths ($p_{H_2O} \cdot L$) and at atmospheric pressure were plotted as a function of temperature. The measurements were performed using the same apparatus as used in the CO_2 work [12]. A few years later, Hottel and Egbert [9] realized that their measurements – among the ones from Eckert [13] and Eberhardt [14] – possessed substantial errors due to wrong temperature measurements and the presence of a layer of room temperature moisty air in the space between the hot gas and the thermopile. Therefore, Hottel and Egbert [9] repeated their measurements, but this time using a new furnace in which the optical path length could be altered. They also used measurements of Schmidt [15], Hottel and Mangelsdorf [12], and Eckert [13]. Hottel and Egbert [9] produced graphs showing the variation of total emissivity as a function of the product $p_{H_2O} \cdot L$ at different temperatures. These graphs indicated that total emissivity was dependent not only on temperature and pressure path length (as it was the case for CO_2), but also on water vapor partial pressure p_{H_2O}. Hottel and Egbert concluded that "the best correlation from an engineering standpoint would consist in expressing water-vapor emissivity as a function of T_g and P_WL[2] as before, but at a partial pressure $P_W = 0$; and then allowing for the effect of actual partial pressure P_W in a separate term multiplying the emissivity previously determined" [9]. In order to find a proper correction factor, they produced graphs showing total gas emissivity as a function of water vapor partial pressure at different path lengths, no matter at what temperatures these curves were made. Then, for any family of curves with fixed $p_{H_2O} \cdot L$ value, the lines were moved vertically and keyed together at a point closest to $p_{H_2O} = 0$. Although an effect of temperature was visible, it was neglected since it was small. Using these curves, the first (partial) pressure correction graph was obtained, which is shown in Fig. 3. Again, each curve at fixed $p_{H_2O} \cdot L$ value is an average of around five (slightly) different curves at different temperatures. Figure 3 is important since it was the principle chart for scaling all available measured emissivities to zero partial pressure, so that by smoothing as well as logarithmic inter- and extrapolations of the scaled emissivities, Fig. 1 was finally obtained.

2.3. Pressure correction charts for H_2O

Figure 3 is valid at total pressure of 1.01325 bar (1 atm) only. For the extension to pressures different from 1.01325 bar,

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[2] P_W stands here for partial pressure of water vapor.