



Absorption of infrared radiation by carbon monoxide at elevated temperatures and pressures: Part B. Total emissivity charts and correlations



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ABSTRACT

The line-by-line procedure developed in the associated paper (Part A) has been used to generate the total emissivity chart for pure CO and CO – N₂ / air mixtures at 1 bar total pressure, in the 300 to 3000 K temperature and 0.01 to 3000 bar cm pressure path length range. Methods of scaling the emissivity to pressures different to 1 bar, in the range 0.1 to 40 bar, are provided through pressure correction graphs and EXCEL interpolator (Supplementary Material). The interpolated emissivities are within ±2% margin from the line-by-line calculated values. The newly developed emissivity graphs are substantially more accurate than the existing Ulrich (1936) & Hottel (1954) and Abu-Romia & Tien (1966) charts.

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1. Introduction and objectives

Emissivity charts concerning water vapor and carbon dioxide can be found in many textbooks, e. g. see Refs. [1–6]. The charts are based on the pioneering work of Hottel and co-workers (see Ref. [7]) and are often used not only in engineering calculations of radiative heat transfer but they are also cited in heat transfer lectures all over the World. Most of the textbooks show the emissivity charts (including pressure correction) for water vapor and carbon dioxide; the charts for other gaseous species (NH₃, SO₂) are shown in Ref. [5] only. Besides their relevance in combustion, these charts are required in conjunction with gasification technology, for example they are needed in the design of entrained flow gasifiers [9]. During gasification processes a large amount of carbon monoxide (CO) is produced and a proper emissivity chart for this species is missing in modern textbooks, although Hottel and his co-workers [7,10] have presented such a chart. This chart is based on the work of Ullrich [11] and is shown in Fig. 1. Ullrich [11] has also presented a pressure correction chart, see Fig. 2, which does not appear in the work of Hottel & Sarofim [7].

The objective of our work is to re-create the carbon monoxide standard emissivity chart and the pressure correction chart using the procedure developed and validated in Part A [12]. We review

the work of Ullrich in Section 2 and explain the origin of both, the standard emissivity as well as the pressure correction charts. The work of Abu-Romia & Tien [13] is also presented in this context. Finally, we present our results in kind of easy-to-use paper graphs and also as look-up tables for high accuracy gray radiation calculations.

In this paper we consider both pure CO and CO/N₂ (or CO/air) mixtures. Before proceeding any further, it is worth recalling that a distinction is made between standard and total emissivities and appropriate definitions can, for example, be found in Alberti et al. [8]. The standard emissivity (ϵ^0) of absorbing / emitting gas “i” in a mixture with broadening-gases is the total emissivity (ϵ^{tot}) of the mixture at ambient pressure ($P_t = 1$ atm) assuming that the collisions between the own molecules (self-broadening) are replaced with collisions between gas “i” and nitrogen (or air). In this context, the standard emissivity of pure CO is the total emissivity at $P_t = 1$ atm with CO – CO self-broadening being replaced with CO – N₂ / air broadening. Since CO-CO broadening is almost identical to CO – N₂ / air broadening (see Section 4), there is hardly any difference between the standard and total emissivities at 1 atm total pressure for pure CO and for CO – N₂ / air mixtures. Such defined standard emissivity (ϵ^0) is used to calculate total emissivity (ϵ^{tot}), at total pressures different to ambient pressure, through the relationship (e. g. see Refs. [7,8,14])

$$\epsilon^{\text{tot}}(T, P_t, p_{\text{CO}}, p_{\text{CO}} \cdot L) = C(T, P_t, p_{\text{CO}}, p_{\text{CO}} \cdot L) \cdot \epsilon^0(T, P_t = 1 \text{ atm}, p_{\text{CO}} \cdot L) \quad (1)$$

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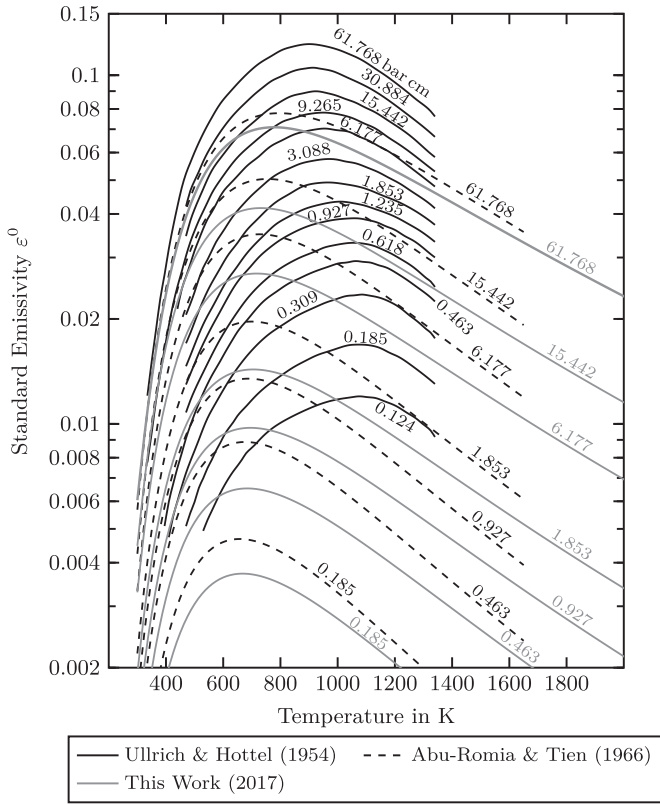


Fig. 1. Ullrich & Hottel's principal chart for carbon monoxide (adapted from Hottel [10] and converted to SI units), Abu-Romia & Tien's chart [13] (Fig. 22 of Ref. [13]), and values calculated in this work. Total pressure is $P_t = 1.01325$ bar (1 atm).

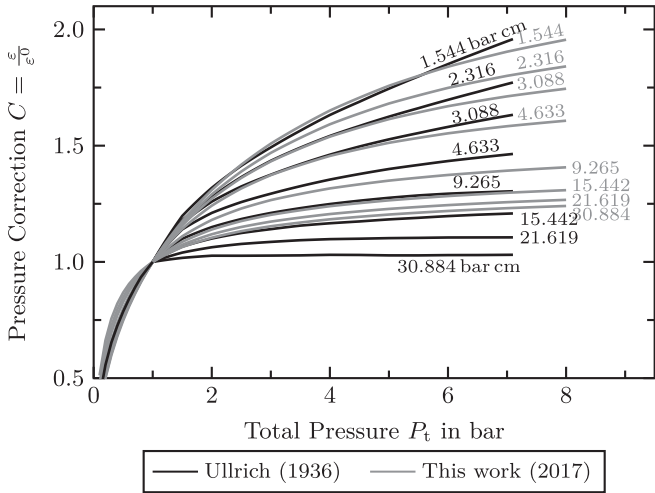


Fig. 2. Ullrich's pressure correction [11] and values generated in this work.

where C is the pressure correction factor. In order to simplify the above relationship further, the total pressure (P_t) and the CO partial pressure (p_{CO}) are combined into an equivalent pressure (P_E) which for CO molecule takes a very simple form (see Section 4)

$$P_E^{CO} = P_t \quad (2)$$

We merely recall that the equivalent pressures for CO_2 and H_2O are calculated as [8,14]

$$P_E^{CO_2} = P_t + 0.28 \cdot p_{CO_2} \quad (3)$$

$$P_E^{H_2O} = P_t + 5.00 \cdot p_{H_2O} \quad (4)$$

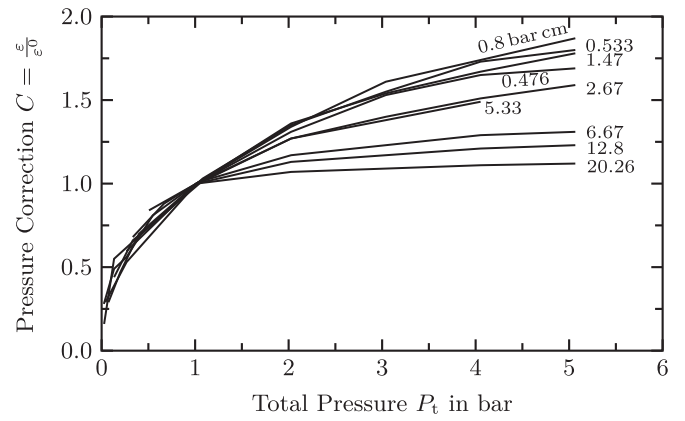


Fig. 3. Eva von Bahr's [16,17] pressure correction factors for carbon monoxide's absorptivity (taken from Ullrich [11] and converted to SI units).

Thus, the goal of this paper is to produce charts showing the standard emissivity $\epsilon^0(T, P_t = 1 \text{ atm}, p_{CO} \cdot L)$ and the pressure correction $C(T, P_t, p_{CO}, p_{CO} \cdot L)$ for temperatures approaching 3000 K and total pressures up to 40 bar.

2. Previous work concerning CO emissivity charts

To our best knowledge, there have been two attempts to generate CO emissivity graphs only. Fig. 1 shows the graphs produced by Ullrich & Hotel [10,11] and Abu-Romia & Tien [13] which are accompanied by our calculations (see Section 3). We begin with Abu-Romia & Tien who in 1966 [13] published measurements of spectral transmissivities of pure CO at 0.5, 1.01, 2.03 and 3.04 bar pressures and temperatures of 300, 600, 900, 1200, and 1500 K at 10 and 20 cm path length for both the fundamental and the 1st overtone bands (limited data concerning absorbance of the fundamental band at 1 cm and 5 cm path length was also provided). The spectral data for the 10 and 20 cm length were used in the development of the model / correlation for the integrated total emissivity of carbon monoxide; the model is shown in Appendix A. The predictions of the model (Appendix A) at $P_t = 1$ atm are plotted in Fig. 1 as Abu-Romia & Tien (1966) standard emissivities (see also Fig. 22 in Ref. [13]).

The standard emissivity chart of Ullrich & Hottel (1954) [10] shown in Fig. 1 is based on the experimental work of Ullrich (1936) [11] who was a Ph.D. student of Hottel. Ullrich used the furnace originally developed by Hottel and Mangelsdorf [15], to measure total emissivity at various temperatures and partial pressures of CO [11]. The furnace had a length of 51.2 cm so that the pressure path length, $p_{CO}L$, was varied by changing the partial pressure of carbon monoxide, p_{CO} . Carbon monoxide was generated by formic acid decomposition at around 450 K. The water vapor of the product gas was condensed in a cooling coil and a sodium hydroxide scrubber was used to neutralize both formic acid vapor and carbon dioxide [11]. By varying the carbon monoxide partial pressure, Ullrich [11] was able to carry out the measurements in the $p_{CO}L$ range from 0.102 to 51.2 bar cm while the temperature was varied in the 477 to 1255 K range.

The furnace was designed for atmospheric pressures so that no measurements at elevated pressures were feasible. For scaling the measured (standard) emissivities to pressures different from 1 atm, Ullrich presented a graph shown in Fig. 2. The graph was based on Eva von Bahr's [16,17] correction factors shown in Fig. 3. By comparing Fig. 3 with Ullrich's chart (Fig. 2) one can identify two assumptions of Ullrich. Firstly, for pressures below atmospheric, a single curve was used in Fig. 2 since, in this pressure range, the dependence with pressure path length was weak in Eva von Bahr's

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