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A simple correlation to estimate natural gas thermal conductivity

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ABSTRACT

A general investigation of the thermal conductivity of natural gas as a function of temperature, pressure and composition was carried out to develop a generalized correlation. The model obtained was based on 731 data points of 42 binary mixtures in wide ranges of pressures (0.1–300 MPa), temperatures (220–425 K) and specific gravities (0.626–1.434). Correction terms for non-hydrocarbons of carbon dioxide and nitrogen were up to 87.8 and 82.8 of mole percent, respectively. The arithmetic average of the model's absolute error was found to be 5.69%, which is acceptable in engineering calculations.

1. Introduction

Natural gas is one of the most important primary energy sources, accounting for almost one-fourth of the world's primary energy consumption (Dudley, 2013). Even though natural gas is a fossil fuel, it is comparatively environmentally sound, and due to its longer estimated future availability compared to oil, it is gaining in importance.

The thermal conductivity of natural gas is one of the thermophysical properties that inevitably enters into mathematical models of real systems used in the design of natural gas processing because of its influence on heat-transfer capability. The thermal conductivity of natural gas is used to determine its combustion properties (Loubar et al., 2005; Rahmouni et al., 2003) and sulfur components (Tuan et al., 1994).

The thermal conductivity of natural gas is generally very low, and normally rises with temperature and pressure (Rojey et al., 1994). The most common experimental methods to measure thermal conductivity of light hydrocarbon mixtures is the transient hot-wire technique (Healy et al., 1976). Currently thermal conductivity sensors are used in the analysis of light hydrocarbon mixtures (Puente et al., 2005; Udina et al., 2008; Takamatsu et al., 2014). However, it is not practicable to measure the thermal conductivity of natural gas (De Groot et al., 1974; Moghadasi et al., 2008).

In natural gas engineering, the graphical correlation for the thermal conductivity of natural gas mixtures is based on the two-step method set out in the Gas Processors and Suppliers Association Engineering Data Book (2004). In the first step, the thermal conductivity at atmospheric pressure is estimated using the apparent molecular weight of the natural gas and the temperature at which the thermal conductivity is desired. In the second step, the ratio of the thermal conductivity of the gas at the desired temperature and pressure to that at atmospheric pressure is obtained using the pseudo reduced pressure and pseudo reduced temperature of the gas at the conditions required. However, there is no reliable engineering model to estimate natural-gas thermal conductivity (Katz and Lee, 1990); thus, an accurate predictive model is needed. The purpose of the current study is to obtain a new accurate, simple, explicit correlation for calculating the thermal conductivity of natural gas based on data in the literature, even when the composition is unknown, over a wide range of pressures (0.1–300 MPa), temperatures (220–425 K) and specific gravities (0.626–1.434).

2. Development of the new model

Natural-gas thermal conductivity has been extensively studied (Gilmore and Comings, 1966; Carmichael et al., 1968; Rosenbaum and Thodos, 1969; Christensen and Fredenslund, 1979; Kestin et al., 1982a,b; Kestin and Nagasaka, 1982; Yorizane et al., 1983; Pátek et al., 2003, 2005), due to its scientific and technological interest. Table 1 lists the thermal conductivity data used in this study.

In this study, the thermal conductivity of natural gas is expressed as a function of dilute-gas thermal conductivity, pseudo

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Table 1
Properties of natural-gas data used in the study (data from Gilmore and Comings, 1966; Carmichael et al., 1968; Rosenbaum and Thodos, 1969; Christensen and Fredenslund, 1979; Kestin et al., 1982a,b; Yorizane et al., 1983; Pátek et al., 2003, 2005).

Property	Min	Max
C_1	0	0.925
C_2	0	0.813
n-C_4	0	0.606
N_2	0	0.828
CO_2	0	0.878
P (psi)	14.503	44087.84
T (°R)	398.376	765
λ (Btu/ft.hr.°F)	0.0109782	0.12781296
Mw (γg_{Mix})	18.14 (0.62)	41.54 (1.43)

$$P_{PC} = \frac{P^{**}_{pcMix}T^{**}_{pcMix}}{T^{**}_{pcMix} + y_{H_2S}(1-y_{H_2S})\left(120\left((y_{CO_2}+y_{H_2S})^{0.9} + (y_{CO_2}+y_{H_2S})^{1.6}\right) + 15\left(y^{0.5}_{H_2S}+y^{4}_{H_2S}\right)\right)} \quad (8)$$

reduced pressure and pseudo reduced temperature (Heidaryan et al., 2013; Jarrahian and Heidaryan, 2012).

$$\lambda = f(\lambda_{1atm}, P_{pr}, T_{pr}) \quad (1)$$

Hydrocarbon-gas specific gravity (γ_{gMix}) is the simple standard measure for natural gases (Edwards, 1917; Weymouth et al., 1923; Civan, 1989). All gas properties needed in this study's calculations can be determined when the specific gravity is given. Thus compositional data has been converted as shown in Equation (2).

$$\gamma_{gMix} = Mw^{-1}_{air}\sum y_i Mw_i \quad (2)$$

In the present study, Standing's procedure (Standing, 1981) was used as an appropriate method to determine pseudocriticals. The concentrations of impurities are easily measurable through field methods like length-of-stain detector tubes (ASTM D4810-06, 2011; ASTM D4984-06, 2011); therefore pseudocriticals of the mixture could be considered for measuring the amount of non-hydrocarbons. The hydrocarbon portion of the total-gas gravity and the hydrocarbon-gas gravity are determined using Equation (3).

$$\gamma_{gHC} = \frac{\gamma_{gMix} - \frac{M_{N_2}y_{N_2} + M_{CO_2}y_{CO_2} + M_{H_2S}y_{H_2S}}{M_{air}}}{1 - y_{N_2} - y_{CO_2} - y_{H_2S}} \quad (3)$$

The quadratic equations of Sutton (2007) are representative over the entire range of natural-gas gravity (Equations (4) and (5)).

$$P^*_{pc} = 671.1 + 14\gamma_{gHC} - 34.3\gamma^2_{gHC} \quad (4)$$

$$T^*_{pc} = 120.1 + 429\gamma_{gHC} - 62.9\gamma^2_{gHC} \quad (5)$$

The pseudocriticals of the whole gas mixture are then as shown in Equations (6) and (7).

$$P^{**}_{pcMix} = (1 - y_{N_2} - y_{CO_2} - y_{H_2S})P^*_{pcHC} + y_{N_2}P_{cN_2} + y_{CO_2}P_{cCO_2} + y_{H_2S}P_{cH_2S} \quad (6)$$

$$T^{**}_{pcMix} = (1 - y_{N_2} - y_{CO_2} - y_{H_2S})T^*_{pcHC} + y_{N_2}T_{cN_2} + y_{CO_2}T_{cCO_2} + y_{H_2S}T_{cH_2S} \quad (7)$$

The mixture pseudocriticals should be adjusted for their CO_2 and H_2S content by means of the Wichert and Aziz (1972) method (Equations (8) and (9)).

Table 2
Tuned coefficients used in Equations (13)–(16).

Coefficient	Tuned coefficient	Standard error
A_1	$3.095251494612 \times 10^{-05}$	$3.0499646171 \times 10^{-05}$
A_2	$-3.054731613002 \times 10^{-01}$	$1.6432783014 \times 10^{-06}$
A_3	$1.205296187262 \times 10^{-02}$	$1.3093647150 \times 10^{-03}$
A_4	$-2.155542603544 \times 10^{-02}$	$8.0259602783 \times 10^{-02}$
A_5	$1.695938319680 \times 10^{-02}$	$8.6339705239 \times 10^{-04}$
A_6	$1.983908703280 \times 10^{-03}$	$1.4060740238 \times 10^{-03}$
A_7	$1.469572516483 \times 10^{-02}$	$8.2247001413 \times 10^{-04}$
A_8	$-7.570807856000 \times 10^{-04}$	$1.3892154673 \times 10^{-03}$
A_9	$1.854452341597 \times 10^{+00}$	$2.1427465393 \times 10^{+02}$
A_{10}	$-1.275798197236 \times 10^{-03}$	$1.2993937966 \times 10^{+02}$
A_{11}	$1.925784814025 \times 10^{-01}$	$9.8979603429 \times 10^{-01}$

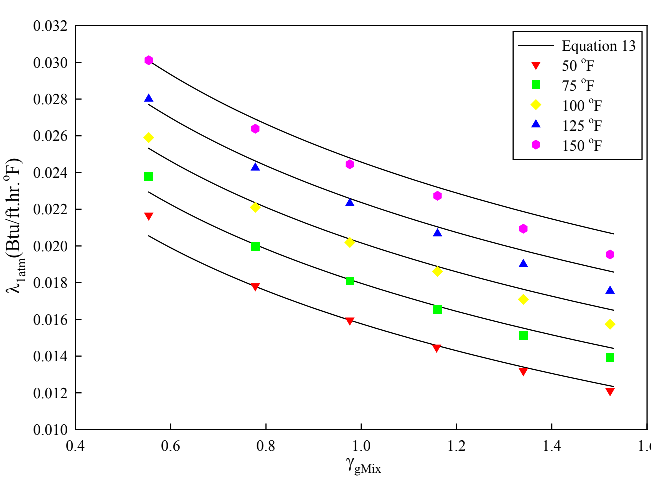

Fig. 1. Predicted results of Equation (13) in comparison with the experimental data for the atmospheric thermal conductivity of natural gas.