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A fast calculation method of thermodynamic properties of variable-composition natural gas mixtures in the supercritical pressure region based on implicit curve-fitting

Tingting Wang, Chao Ding, Guoliang Ding*, Dan Zhao, Tao Ren

Institute of Refrigeration and Cryogenics, Shanghai Jiao Tong University, Shanghai 200240, China

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ABSTRACT

Vaporizers are widely used to re-gasify the liquefied natural gas which consists of variable compositions at supercritical pressures. The duration of vaporizer design based on simulations severely depends on the calculation speed of thermodynamic properties of natural gas due to millions of thermodynamic property iterations. This paper presents a fast calculation method of thermodynamic properties of natural gas in supercritical pressure region. In this method, a calculation model for a reference composition is established at first, by dividing the supercritical pressure region into three subsections and regressing each subsection separately based on implicit curve-fitting; and then composition based implicit curve-fitting equations are developed to extend thermodynamic property calculation from the reference composition to any variable compositions. With this method, the equations for typical compositions of natural gas including C_1, C_2, C_3, n-C_4, n-C_5 and N_2 are presented, covering the temperature range from −170 °C to 60 °C and the pressure range from 5 MPa to 10 MPa. The present method is about 10^4 times faster than GERG-2008, and the mean deviation is less than 0.5%.

1. Introduction

Natural gas (NG) is a clean fuel and is often liquefied for transportation (Hammer, 2004). The liquefied NG (LNG) must be re-gasified to NG under supercritical pressure conditions by vaporizers before it is used as fuel gas (Han et al., 2016a). The vaporizer efficiency seriously impacts the reliability of LNG re-gasification process and operating cost, and thus design of efficient and reliable vaporizers is in great demands (Fahmy et al., 2015).

For designing LNG vaporizers, the simulation based design method is an effective and low cost approach compared with the experiment based design method (Pacio and Dorao, 2011). The simulation based design method for LNG vaporizers, e.g. the distributed-parameter models for LNG vaporizers (Pan et al., 2016; Pu et al., 2014; Qi et al., 2016), will call huge times of thermodynamic property calculations which directly determine the speed and accuracy of the design of the vaporizers (Melaaen and Owren, 1996; Zudkevitch and Gray, 1975). Therefore, it is necessary to develop a fast calculation method for thermodynamic properties of NG in the vaporizers that satisfies the requirements of fast speed, high accuracy, absolute stability and reversibility (Ding et al., 2005).

NG in the vaporizers has two distinguishing features including operating under supercritical pressures and consisting of variable composition. Firstly, NG needs to be pressurized to supercritical pressures before entering the vaporizers to reduce the power consumption of pumping LNG, and the pressure range is from 5 to 9 MPa in the existing vaporizers (Han et al., 2016a; Meng et al., 2014a; Meng et al., 2014b). Secondly, NG is a mixture of several different components, and the composition of NG varies with the gas fields (Foeg et al., 1998). Therefore, a fast calculation method for thermodynamic properties of NG in the vaporizers is required to be capable of calculating the thermodynamic properties of variable-composition NG in the whole supercritical pressure region.

As one of the existing methods for calculating the thermodynamic properties, the equation of state (EOS) method, e.g. Peng-Robinson EOS (Peng and Robinson, 1976), Redlich-Kwong-Soave EOS (Soave, 1972), Lee-Kesler-Plöcker EOS (Lee and Kesler, 1975; Plocker et al., 1978) and GERG-2008 (Kunz and Wagner, 2012), is widely used in the steady-state LNG process calculation based on simplified material and heat balance equations, due to its best accuracy over a large region among all the methods. However, the

* Corresponding author.
E-mail address: glding@sjtu.edu.cn (G. Ding).

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Table 1
Comparison of the present method and existing methods.

Methods	Fast speed	High accuracy	Absolute stability	Reversibility
EOS methods	✗	✓	✗	✗
Look-up table methods	✓	✓	✓	✗
Explicit regression methods	✓	✓	✓	✗
Implicit curve-fitting methods	✓	✓	✓	✓

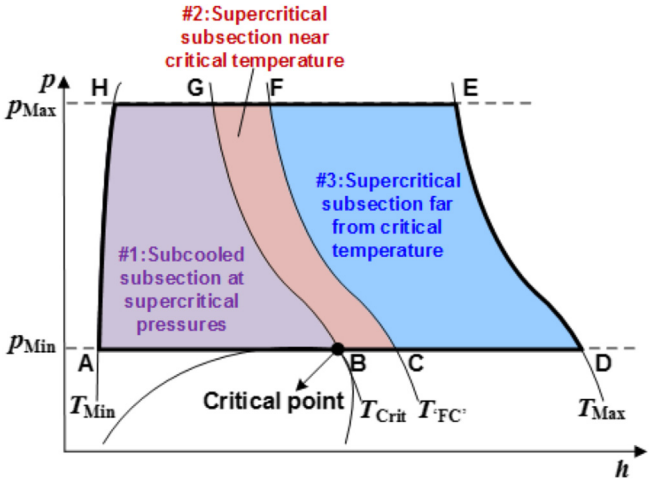

Fig. 1. Schematic diagram of fitting section partition.

calculation speed and stability of the EOS method are limited by unavoidable iterations in solving the equation of state (Ding et al., 2009), and the computation time resulted from the EOS solution is very long when huge times of property calculations are needed, e.g. designing a LNG equipment with a distributed-parameter model (Han et al., 2016b; Pan et al., 2016; Wang et al., 2015).

The look-up table method, consisting of an interpolation scheme and a table usually generated by an equation of state, is a fast calculation way because the equation of state need not be solved after the table is once generated. But the calculation of related parameters such as $h = f(p, T)$ and $T = g(p, h)$, are done based on different tables and these parameters are not reversible (Ding, 2007). Therefore, this method is not suitable for application in millions of thermodynamic property calculations, e.g. simulations of LNG vaporizers.

The implicit curve-fitting and explicit calculation method has been developed for fast and stable calculation of thermodynamic properties of working fluids (Ding, 2007). In this method, an implicit cubic equation is established to ensure the high accuracy and reversibility of curve-fitting, and the analytical solution of the implicit equation is used as the explicit formulae for fast and stable calculation of thermodynamic properties, as shown in Table 1. This method has been well used for pure refrigerants (e.g. R22, R134a and R32) and mixed refrigerants with fixed compositions (e.g. R410A and R407C) (Ding et al., 2005; Sieres et al., 2012; Zhao et al., 2009). The application range of this method covered the saturated region, the superheated region, the two-phase region and the

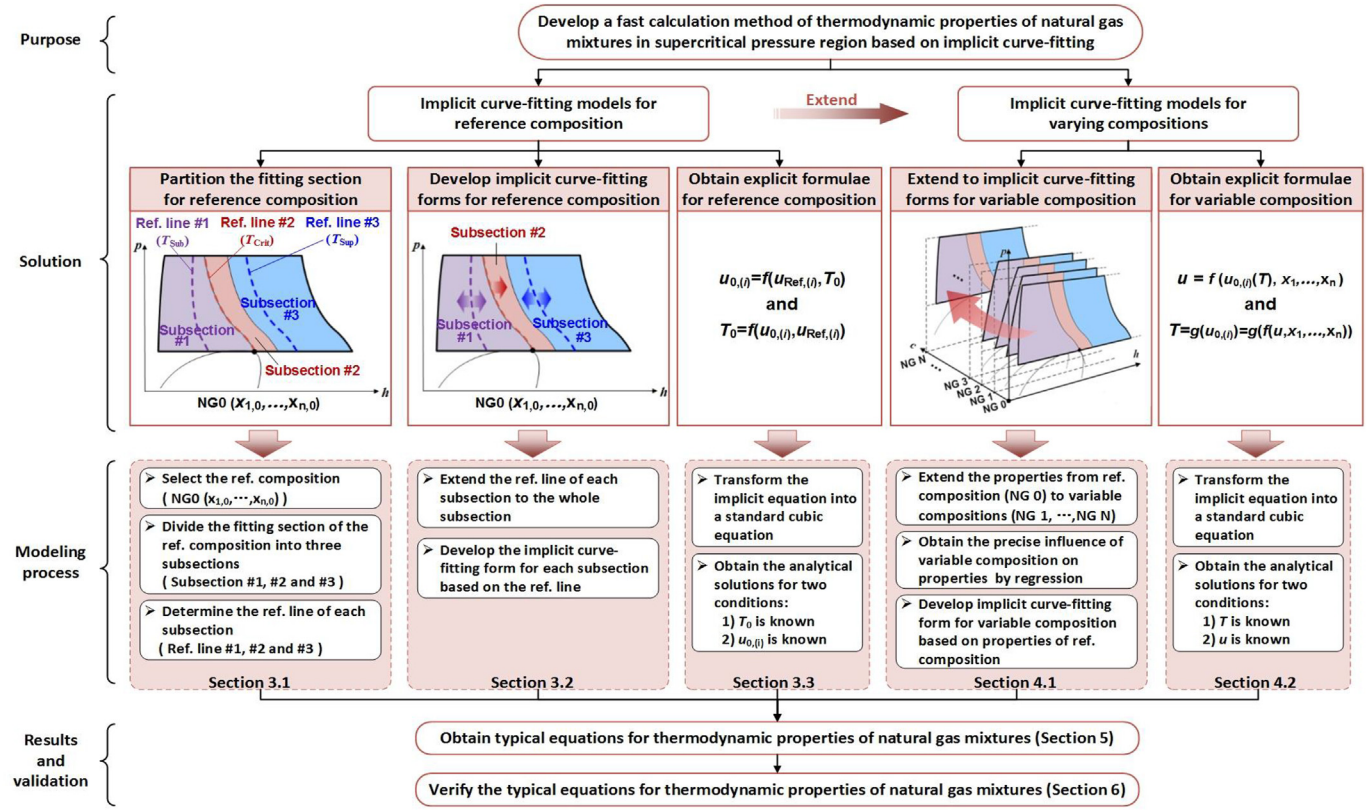

Fig. 2. Road map of this study.