Applied Thermal Engineering 51 (2013) 177–189

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Unsteady-state thermal calculation of buried oil pipeline using a proper orthogonal decomposition reduced-order model

Guojun Yu [a], Bo Yu [a,*], Dongxu Han [a], Liping Wang [b]

[a] Beijing Key Laboratory of Urban Oil and Gas Distribution Technology, China University of Petroleum, Fuxue Road 18, Changping, Beijing 102249, PR China

[b] Petroleum Development Center of Shengli Oilfield, Dongying 257100, PR China

HIGHLIGHTS

► A general reduced-order model is established for thermal process of oil pipeline.
► The proposed method is much faster than finite-volume method.
► The proposed method is accurate enough for engineering applications.
► The proposed method provides a fast design tool.

ARTICLE INFO

Article history:
Received 9 July 2012
Accepted 3 September 2012
Available online 11 September 2012

Keywords:
Proper orthogonal decomposition (POD)
Unstructured grids
Buried oil pipeline
Unsteady-state thermal calculation

ABSTRACT

The POD-Galerkin reduced-order model is established for the thermal process of the buried oil pipeline, which carries complex and inhomogeneous boundary conditions, including Dirichlet (or first-type), Neumann (or second-type), and Robin (or third-type) boundary conditions. Especially, the treatment of different boundary conditions is given in detail. The implementation of POD-Galerkin reduced-order model on unstructured mesh is also introduced. Subsequently, the thermal processes of batching transportation and commissioning in an oil pipeline are calculated by the established reduced-order model, indicating that the reduced-order model is accurate and efficient. The application of this reduced-order model may provide a convenient and rapid approach for the design and ensuring safe and economic operation of the oil transportation pipeline.

1. Introduction

A large proportion of crude oil produced in some countries or regions are of high pour point and high viscosity. For example, the high pour point and high viscosity crude oil produced in China account for over 80%. Due to poor fluidity, this kind of crude oil has to be heated during pipeline transportation to ensure safe operation. Therefore, this heating transportation entails the thermal calculation for the design, commissioning and operation of oil pipelines. At present, analytic methods and empiric formulas fall far short of demand for the thermal calculation of complex unsteady-state process of the pipeline system, thus numerical method has to be resorted to in this case.

One problem facing the numerical method is the efficiency of the calculation. The accuracy of numerical simulation depends on the density of the mesh, and high-quality grids usually produce reliable solutions when grid independent solution is obtained. However, the cost is an increased number of equations to be solved, leading to long computing time and high storage requirements.

A safe and economic operation mode is vitally important in oil transportation engineering, which can be achieved by comparing the performances of different modes under various scenarios. It would be impossible or costly to carry out laboratory experiments or field tests to obtain optimized operation modes, and naturally numerical simulation becomes a substitute. Sometimes, the calculations for different operation modes by numerical methods are time-consuming. In addition, when the real-time solutions of transient heat transfer process of the oil pipeline are concerned, we employ a time-stepping procedure, in which explicit schemes are seldom used because of the time step limitation. However, implicit schemes require solution of a set of equations at each time step. If the solutions are sought for longer time instants, the cost of time-stepping procedure would be huge. Thus, exploring an efficient and accurate method for the thermal calculation of oil pipeline system is very important and bears practical significance.

* Corresponding author. Tel.: +86 1089733849.
E-mail address: yubobox@vip.163.com (B. Yu).

1359-4311/$ – see front matter
http://dx.doi.org/10.1016/j.applthermaleng.2012.09.005

Nomenclature

A	cross-section area of the pipeline (m^2)
$c_i(\tau)$	magnitude corresponding to ith basis function
C_k	heat capacity of the pipe wall ($k = 1$) and soil ($k = 2$) (J/(kg °C))
C_p	heat capacity under constant pressure of the crude oil (J/(kg °C))
D	inner diameter of the pipeline (m)
f	Darcy friction coefficient
g	gravity acceleration (m/s^2)
h	specific enthalpy of the crude oil (J/kg)
M	number of basis functions employed
p	average pressure on the pipeline cross section (Pa)
q	heat loss of the crude oil on unit area of the pipe wall during $\Delta\tau$ time (W/m^2)
R_0	inner radius of the oil pipeline (m)
s	elevation difference (m)
T_a	air temperature (°C)
u	specific energy of the crude oil (J/kg)
V	average velocity of the crude oil (m/s)
z	axial direction of the pipeline (m)

Greek symbols

α_o	heat transfer coefficient of the pipe flow ($W/(m^2\,°C)$)
α_a	heat transfer coefficient at the ground surface ($W/(m^2\,°C)$)
β	expansion coefficient of the crude oil ($°C^{-1}$)
λ_k	conductivity of the pipe ($k = 1$) and the soil ($k = 2$) (W/(m °C))
ρ	density of the crude oil (kg/m^3)
ρ_k	density of the pipe ($k = 1$) and soil ($k = 2$) (kg/m^3)
ϕ_i	ith basis vector
Ψ	oil temperature (°C)
$\widehat{\Psi}(i)$	oil temperature calculated by POD at computational node i
$\Psi(i)$	oil temperature calculated by FVM at computational node i
τ, $\Delta\tau$	time and time interval, respectively (s)

Subscript

o	oil
a	air
av	average
c	constant

A few techniques have been proposed to accelerate the solution procedures of numerical method, such as parallelization, multigrid iterative solvers, domain decomposition and so on. In addition, statistics has offered an efficient technique for detecting the correlations existing in large data sets, then eliminating information overlapping of the samples, thus reducing the order of the interested problem. This technique is known as Proper Orthogonal Decomposition (POD), also known as Karhunen–Loève Decomposition (KLD), Principal Component Analysis (PCA) or Singular Value Decomposition (SVD). This method essentially provides orthogonal bases for representing the given data in a certain least squares optimal sense; that is, it provides a way to find optimal lower dimensional approximations of the given data. From the perspective of geometric interpretation, POD can be seen as a technique for approximating a set of vectors using a rotated orthogonal coordinate frame [1]. The angles of rotation are selected in such a way that the projections of the vectors on subsequent coordinate axes decay in the most rapid way. Therefore, only the few first projections are needed to approximate all vectors constituting the set. The directions of the rotated coordinate axes are termed the POD basis.

The history of proper orthogonal decomposition (POD) can date back to 100 years ago by the work of Pearson [2]. At that time, POD was used as a tool of processing statistical data. Since then the technique has undergone several times developments in various fields including: signal processing and control theory [3,4], weather prediction, oceanography, data compression and storage, inverse problems [5,6], biological engineering [7] and many others. Another important application of POD is in turbulence [8,9]. It was firstly introduced by Lumley [9] into this area and used to detect the spatial large-scale organized motions. Some detailed description regarding POD theory can also be found in Ref. [10].

In the interested field of this paper, POD is usually combined with finite element method (FEM) to construct a reduced-order model [1,11–13]. This reduced-order FEM can effectively accelerate the calculation. To the author's knowledge, studies on the combination of POD and finite volume method (FVM) are very limited. Among the few references, Raghupathy et al. [14] established the boundary-condition-independent reduced-order model for complex electronic packages by the POD-Galerkin methodology. Their reduced-order model is capable of accurately predicting solutions over a wide range of boundary conditions because of the truly boundary-condition independent nature of the obtained reduced-order model. Astrid [15] introduced the application of POD-Galerkin reduced-order model to heat conduction problem in detail. However, the boundary conditions of the reduced-order model included in relevant references are mainly the first-type and second-type boundary conditions, and the third-type boundary condition rarely involves. Besides, the treatments of different boundary conditions are seldom described in detail. In addition, the reduced-order models in relevant references are always based on uniform structured meshes, while combination of POD and FVM based on unstructured meshes is rare. Actually, there are a few differences between the POD-Galerkin reduced-order model on uniform meshes and that on unstructured meshes, thus there are some notable details.

This study focuses on how the Proper Orthogonal Decomposition (POD)-Galerkin methodology can be used with the finite volume method to establish reduced-order models. Especially, the treatments of different boundary conditions in the reduced-order model will be discussed in detail. Besides, the implementation of POD-Galerkin reduced-order model on unstructured mesh is to be introduced. Afterward, the unsteady-state thermal process of the oil pipeline will be calculated by the POD-Galerkin reduced-order model.

The layout of this paper is as follows: The descriptions of the physical problem and mathematical models used to calculate the snapshot matrix are given before hand. Then the theory and fundamentals of POD are presented. Thereafter, POD-Galerkin reduced-order model for the unsteady-state thermal process of oil transportation pipeline is established in detail. Lastly, the accuracy and efficiency of POD-Galerkin reduced-order models is demonstrated by two practical examples in oil transportation engineering.

2. Physical problem and mathematical model

2.1. Description of the physical problem

Based on the analysis of the thermal process of buried oil pipeline system, we abstract the physical model from the physical problem, as shown in Fig. 1. In Fig. 1, the influence region of the pipeline on X-axis and Y-axis are $2L$ and H respectively, where