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Research Paper

A fluid-structure coupling method to obtain parameter distributions in a combustion chamber with moving boundaries

Chaobin Hu, Xiaobing Zhang*

School of Energy and Power Engineering, Nanjing University of Science and Technology, China

HIGHLIGHTS

- A coupled method is provided to update fluid fields in a gun propelling process.
- The coupling strategy dealing with moving boundaries is effective.
- The irregularly distributed pressure is considered in the coupled method.
- The resistance on the projectile varies with the radial deformation of the barrel.

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ABSTRACT

A fluid-structure coupling method was put forward to obtain parameter distributions in a fluid field induced by the combustion of energetic materials. A one-dimensional two-fluid model was utilized to govern the transient combustion. The nonlinear mechanical behaviors were predicted basing on the engineering software ABAQUS. Different from most of the existed studies, we coupled the fluids and the structures through moving boundaries by using a user subroutine interface *VUAMP* in ABAQUS and realized the application of an irregularly distributed pressure by using a user subroutine interface *VDLOAD*. The coupling approach was validated by comparing the predicted results with analytical solutions and experiments. Based on the validated approach, parameter distributions in the combustion chamber of a large caliber gun were obtained and the influences of the irregularly distributed pressure were further discussed. The results indicated that the coupling approach is capable of obtaining parameter distributions of the fluid field in an expanding combustion chamber. The approach can be applied to provide accurate parameter distributions in determining boundary conditions for the study of transient heat transfer in the chambers.

1. Introduction

Parameter distributions in fluid fields induced by the combustion of energetic materials are pivotal for the study of transient heat transfer in combustion chambers. Fluid fields in engineering systems such as reciprocating piston engines [1,2], projectile propelling systems [3,4] and light gas guns [5] are the examples. Transient effects and high temperature conditions always accompany with the development of the physical fields, which makes it too expensive to investigate the parameter distributions thoroughly by using analytical methods and experimental methods. Therefore, numerical methods should be put forward to study those engineering systems. In the present work, a coupled numerical method, which is fidelity to the inherent mechanism of the physical process, was carried out to obtain the parameter distributions in a gun launching system.

Decades of efforts have been put into establishing mathematical models to investigate the combustion of propellant in gun launching processes. In the early stages, statistical models [6], continuum-mechanics models [7], formal averaging models [8] and two-phase dynamics models [9–13] were put forward to predict the system performances. Different from the other models, the two-phase fluid models can provide parameter distributions in the fluid field. However, the mechanical interactions between the projectile and gun bore are not considered in those models. Due to the strong nonlinearities in the mechanical interactions, analytical methods are powerless in obtaining the solution. Therefore, the mechanical interactions were studied by using experimental approaches [14–17] and numerical methods [18–21].

Considered the high pressure and high temperature conditions in gun bores during launching processes, parameter distributions obtained

* Corresponding author.
E-mail address: zhangxb680504@163.com (X. Zhang).

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Nomenclature

A	cross-sectional area, m^2
c	sound speed, $m\,s^{-1}$
C_0	a non-dimensional constant
D	diameter, mm
e	specific internal energy, $J\,kg^{-1}$
e_1	half of the web thickness, mm
f	propellant force, $J\,kg^{-1}$
f_s	interphase drag, $N\,m^{-3}$
l	the projectile travel
L	length of the chamber, m
$\dot{m}$	rate of mass exchange, $kg\,m^{-3}\,s^{-1}$
n	number of rifles
p	pressure, Pa
p_m	the maximum pressure, Pa
R	gas constant, $J\,kg^{-1}\,K^{-1}$
R_p	intergranular stress, Pa
t	time, s
T	temperature, K
u	velocity, $m\,s^{-1}$
v	projectile velocity, $m\,s^{-1}$
v_0	muzzle velocity, $m\,s^{-1}$
W	width, mm
x	coordinate of the domain, m

Greek symbols

α	covolume, $m^3\,kg^{-1}$
β	forcing cone angle, °
ε	strain
ρ	density, $kg\,m^{-3}$
σ	stress, Pa
φ	porosity
φ_0	bed settling porosity
ω	charge mass, kg
Δt	time step, s
Δx	spatial mesh size, m

Subscripts

B	rotating band
C	combustion
g	gas phase
G	groove
L	land
p	solid phase
ign	igniter

by using numerical methods are critical for the study of transient heat transfer in gun bores [22,23]. Due to the transient effects and the strong nonlinear factors, the interactions between the fluids and the structures were simplified. In the existed fluid models, a constant coefficient was utilized to simplify the resistance caused by the mechanical interactions between the projectile and the barrel. While studying the mechanical interactions, the influences of the irregularly distributed loads applied on the inner wall of the chamber where exposed to the gas products were ignored. In order to improve the fidelity of the obtained parameter distributions, we put forward a coupled method to address the research gaps.

2. Theoretical model

As illustrated in Fig. 1, a gun propelling system is mainly comprised of a projectile, propellant, and a combustion chamber. The chamber is used to contain combustion products and to provide guidance for the projectile. After the propellant is ignited, huge amounts of high pressure and high temperature products are released into the chamber. Meanwhile, the projectile is propelled to interact with the barrel. A propelling process is completed when the projectile is propelled to the muzzle in several milliseconds. During the short duration, the pressure in the chamber reaches several hundred MPa and the maximum temperature reaches about 3000 K. The strong transient effects make it difficult to predict the combustion. Theoretical models governing the fluid field and the mechanical behaviors are presented as following:

2.1. Fluid field induced by the combustion

A large number of propellant particles are charged in the combustion chamber. The combustion of the particles is confined within a domain enclosed by the inner wall of the chamber and the bottom of the projectile. The domain expands along with the forward movement of the projectile. The propellant combustion develops a multi-phase flow field. In the work, we are interested in the parameter distributions along the axis of the barrel. Considering the ratio of length to diameter of the combustion chamber and the related transient effects, we utilized a one-dimensional two-fluid model to govern the fluid field. In the model, the propellant particles are assumed incompressible and the combustion of a single particle is predicted basing on the geometry burning law. The combustion is governed by Eq. (1) in a conservative form.

$$\frac{\partial \mathbf{W}}{\partial t} + \frac{\partial \mathbf{F}}{\partial x} = \mathbf{H} \tag{1}$$

where the vector of conservative variables **W**, the vector of the fluxes **F**, and the vector of the source terms **H** are defined as following:

$$\mathbf{W} = \begin{bmatrix} \varphi\rho_g A \\ (1-\varphi)\rho_p A \\ \varphi\rho_g u_g A \\ (1-\varphi)\rho_p u_p A \\ \varphi\rho_g A\left(e_g + \frac{u_g^2}{2}\right) \end{bmatrix} \tag{2}$$

$$\mathbf{F} = \begin{bmatrix} \varphi\rho_g u_g A \\ (1-\varphi)\rho_p u_p A \\ A\varphi(p + \rho_g u_g^2) \\ A(1-\varphi)(p + R_p + \rho_p u_p^2) \\ \varphi\rho_g u_g A\left(e_g + \frac{p}{\rho_g} + \frac{u_g^2}{2}\right) \end{bmatrix} \tag{3}$$

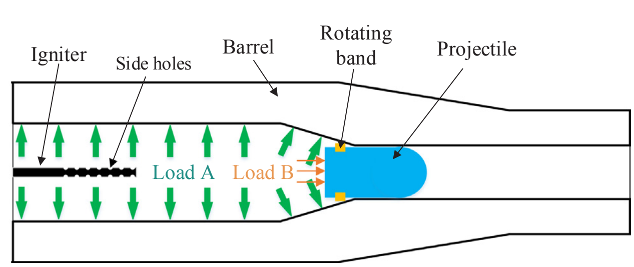

Fig. 1. Illustration of the combustion chamber.

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