Flame propagation through three-phase methane-hydrate particles

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A B S T R A C T

A new mathematical solution for the laminar combustion of a spray containing three-phase particles is derived. The three-phase particles are represented by methane hydrate (MH) particles. These particles melt and evaporate following a spherical symmetric model that demonstrates the unique nature of that process. The methane-hydrate particles are uniformly distributed, yet the gaseous methane is not initially premixed, until they reach the particle depletion front. A one-dimensional, laminar flame then propagates into a homogeneous mixture of oxidizer, inert gases and small methane-hydrate particles. Characteristics of the laminar methane-hydrate spray combustion are examined at different methane-to-water mass ratio values within the particles. The methane-hydrate evaporation model serves as a building block for the evaluation of these characteristics. Previous constraints on the evaporation front are relaxed. Instead, the unique profiles of the evaporation process of the methane-hydrate particles are integrated over the entire evaporation period. Thus, an energy balance is employed to evaluate the flame location, velocity and temperature at which all liquid is evaporated. Using this approach it is shown that modeling the initial transient evaporation stage is crucial in MH and leads to non-linear evaporation characteristics. This in turn alters the dynamics of the supported flame temperature, location and velocity. Particle loading is shown to have significant impact on the evaporation and flame as well.

1. Introduction

1.1. Gas hydrates

Gas-hydrates (GH) are ice-like crystalline solids, consisting of a non-stoichiometric compounds of water cavities and methane gas molecules [1]. At high pressures and low temperatures, different gas molecules can fill the cavities within the ice cage, preventing hydrogen-bond strain and breakage. Different guest-molecules, also known as primers, form different configurations of water cages. The present paper will deal with spray evaporation and combustion of the most common natural gas-hydrate, formed by methane gas molecules.

Gas hydrates can be found at offshore sites, the continental shelves, and at onshore sites, mainly in Alaska, Canada and the Tibetan Plateau [2]. Though still a fossil fuel, gas-hydrates, like other natural gas sources are considered a cleaner source of energy, contributing to the growing demand of natural gas consumption worldwide.

In addition to being a promising energy source, gas-hydrates are considered for natural gas transportation, due to their ability to sustain high gas capacity. For gas hydrates consisting of non-polar hydrocarbons, such as methane, this is a great virtue. For example, about 20–30 ppm methane can be dissolved in water at the relevant temperature and pressure values [3,4], while a methane hydrate particle can contain up to 13.4% of methane (1 methane molecule for each 5.75 molecules of water [1] $Y_{F, MH}$=0.134). Hence, in atmospheric conditions, 1 cubic meter of methane hydrate (MH) is equivalent to about 170 cubic meters.

Thanks to their high capacity, gas-hydrates are considered as means to transport natural gas.

Transportation, as well as other handling procedures could be made easier by exploiting the meta-stable region, also known as the "anomalous region" [2] where hydrates were shown to preserve to the level of about 93% for 24 h [5].

Though industrial use of methane-hydrate as a fuel is still being investigated [6–9], practical concepts and design for production processes were recently suggested, e.g., during oceanic

Latin letters

A	pre-exponent factor
b	water-to-fuel mole ratio for hydrate
$\bar{C}_j$	Evaporation rate of species j within the spray
C_p	constant pressure specific heat
D	diffusion coefficient
E	activation energy
f	flame
F	Fuel
h	specific thermal enthalpy
K_1	evaporation rate
L	latent heat of vaporization
Y	mass fraction
$\dot{m}$	mass flow rate
M	mass
p	pressure
Q	heat of combustion
r	radial coordinate
R	particle radius
R_u	universal gas constant
S	source terms (Eq. (9))
t	time
T	temperature
U	Laminar flame speed
$\dot{w}_i$	reaction rate of species i
x	1D coordinate

Greek letters

α	thermal diffusivity
α_{MH}	particle loading
β	Shvab-Zel'dovich function
η	normalized radial coordinate
λ	thermal conductivity
ν	stoichiometric constant, mass-based
$\bar{\nu}$	stoichiometric constant, mole-based
θ	non-dimensional activation energy
ρ	density
ξ	dimensionless flame coordinate
τ	normalized time
ϕ	equivalence ratio

Subscripts

a	adiabatic
b	burnt
BM	bubbly mixture
BM, s	bubbly mixture-gas interface, on bubbly mixture side
f	flame
F	fuel
g	gas phase
i	the ith species
L	liquid phase
mix	mixture
MH	Methane-Hydrate
o	oxidizer
s	surface value, on gas side of interface
vap	vaporization
w	water
0	initial
∞	ambient value

Superscript

o	reference value
$*$	dimensional

Non-dimensional groups

Da	Damköhler number
Le	Lewis number

methane-hydrate extraction, a combination of depressurization with preheating by waste heat from the power generation system offshore [10].

A recent study analyzes the evaporation process of small, three-phase MH particles [11]. A unique behavior of the MH particles indicates that during the early evaporation period, the outer surface of the MH particles (R_s) progresses, rather than recedes, namely the particle initially swells, rather than shrinks. Throughout the evaporation process, drived by the external heat ($\dot{q}_{g,s}$), the MH particles contain an inner solid core (R_m) (that gradually melts due to $\dot{q}_m$) and a bubbly mixture of gaseous methane and liquid water (between R_m to R_s, see Fig. 1). Both interfaces change their sizes at different rates; thereby the behavior of the surface area of the MH particles will never reach a pure linear variation, as for the $d^2 - law$ as long as the solid core exists. At the last period of evaporation, the bubbly mixture layer becomes very thin and the numerical values of the particle surface come close to a linear variation.

Small methane hydrate particles (0.1..0.3 mm) can be formed by granulation under prescribes pressure and temperature (274 K & 6 MPa) [12]. Continuous production of gas hydrates can be achieved by spraying [13]. For example, Tsuji et al. [14] sprayed water through a gas (at 275 K & 2.9 MPa) to form an H-structure hydrate, though the same technology was used to form different gas-hydrate structures [15,16].

1.2. Laminar spray flames

The single droplet approach was shown to capture the essence of the unique time-dependent thermo-chemical properties of the MH particles undergoing combustion [11]. However, in that study, the authors also noted that one should further examine a cloud of particles. Clearly, the cloud may change the behavior of the individual particle.

The behavior of a spray of particles, which may be viewed as a more realistic description of a fuel in the combustion processes, is not always reflected through the single droplet model [17,18]. Experimental and theoretical studies have shown that group combustion frequently occurs, where excess of fuel in the spray injection region prevents the occurrence of single droplet
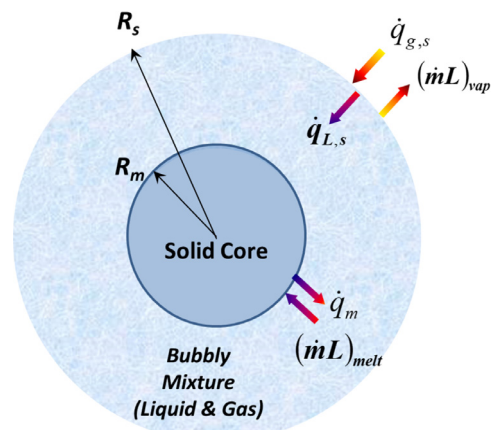

Fig. 1. A schematic description of a typical three-phase, Gas-Hydrate (GH) sphere (based on [11]).