SCALE MODELING OF GAS EXPLOSIONS IN CLOSED VESSELS

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The effect of geometrical dimensions on combustion of gas mixtures in closed vessels with obstacles has been studied. We show the possibility of considering separately the effects of combustion intensification with allowance for flame self-turbulization and the interaction of flame with obstacles. It has been established that the degree of combustion intensification due to self-turbulization is a universal function of the vessel volume and of the physicochemical characteristics of a gas mixture and is controlled by the Froude and Lewis numbers. Scale modeling of the interaction of flame with obstacles is shown to be possible.

The problem of the prediction of the dynamics of an accidental gas explosion within industrial buildings or industrial equipment has a number of specific features. First, there is the variety of concrete conditions. The shape and size of the room and the configuration and location of the equipment are, as a rule, complex and nonstandard. The composition of a combustible mixture, its reactivity, and thermo- and hydrodynamic states can vary over a wide range. Explosions often involve multi-phase and disperse media, and one or several sequential combustion phenomena can be realized in explosion, i.e., laminar and turbulent flame propagation, self-ignition, detonation, etc. Gas compressibility creates favorable conditions for transition of one combustion regime into another, generation of baric waves, the chemical-energy concentration in local volumes, and, consequently, for the development of abnormally high pressures.

These features stimulate the search for different methods of modeling internal uncontrollable explosions, in particular, of scale modeling. Three basic approaches should be mentioned: mathematical, physical, and semiempirical. Mathematical modeling assumes the solution of unsteady-state Navier–Stokes equations and the introduction of some simplifying assumptions, including those on the flow structure and on a method for taking into account chemical reactions. This approach is rather promising. Its adequacy, however, is not always obvious [1, 2]. Physical modeling assumes full-scale experiments and gives more realistic information. It is, however, more expensive and is used only for very important purposes (aviation, nuclear power engineering, etc.) [3]. The semiempirical approach is based on theoretical and experimental data on the internal gas explosion. Its main advantage is a combination of theory and experiment which ensures a successive development of the approach and its effectiveness. This approach can be illustrated by the modeling of venting explosions [4], which is used in many applications [5].

In this work, an attempt is made to perform semiempirical modeling of gas explosions in closed vessels with obstacles in the simplest formulation, i.e., in spherical vessels with obstacles which cause a relatively weak disturbance, and with the use of poorly reacting mixtures.

THEORETICAL FOUNDATION OF SCALE MODELING

The theory of the internal explosion of a homogeneous mixture has been well developed for flames with simple laws of surface evolution [6]. An actual explosion in a vessel with obstacles leads to generation
of turbulence and of jet and vortex flows upon interaction of moving gases with obstacles and also under the action of gravity. The stronger the turbulence or the more developed the flame surface, the higher the integral rate of heat release. The hydrodynamic and thermal-diffusive flame instabilities can also cause a more intense mixture combustion. Thus, the consideration of turbulence (the degree of flame deformation) is of prime importance.

Babkin et al. [7] have considered the problem of deformed and turbulent flame propagation. They have shown that the main dynamic characteristics of the process can be determined using equations for laminar symmetric flames. To this end, one requires information on either the turbulent burning rate \( S_{u,t} \) or the area of the deformed flame surface. These parameters can be found in the literature or obtained experimentally. This conclusion was verified in [7] by the GUI–Michelson principle \( S_{u,t}F = S_uF_t \), where \( S_{u,t} \) is the turbulent burning rate determined on the control surface \( F \), \( F_t \) is the turbulent flame area, and \( S_u \) is the laminar burning rate.

The ratio \( \chi = S_{u,t}/S_u = F_t/F \) means the relative turbulent burning rate or the degree of flame surface deformation. This quantity, which was first mentioned in [8] as a correcting parameter in the problem of a venting explosion, is now often used in the literature [9, 10].

The identity of the equations of laminar and turbulent flame dynamics, which is a consequence of the nondependence of thermodynamic and kinetic equations, allowed one to construct the similarity groups for physical modeling of laminar and turbulent flames [11]. It was shown, in particular, that the characteristics of actual and model explosions with equal \( \pi, \pi_e, \gamma_u \), and \( \gamma_l \) values are related by the expression

\[
\frac{d\pi}{dt} = \frac{(S_{u,t})_r}{(S_u)_m} \frac{R_m}{R_r} \frac{d\pi}{dt}_m, \tag{1}
\]

where \( \pi = P/P_t \) and \( \pi_e = P_e/P_t \) (\( P, P_t \), and \( P_e \) are the instant, initial, and end explosion pressures, respectively); \( R \) is the radius of the vessel; and \( \gamma_u \) and \( \gamma_l \) are the adiabatic exponents for the fresh and burnt gases; the subscript \( r \) refers to the actual explosion, and \( m \) to the model explosion.

For the problem of scale modeling, we write Eq. (1) as

\[
\pi' = \pi'_m \chi, \tag{2}
\]

where \( \pi' = d\pi/d\tau \) and \( \tau = tS_u/R \). The value of \( \chi \) characterizes the degree of burning-rate increase in the actual vessel with obstacles relative to the laminar burning rate in the empty model vessel.

Dividing both sides of Eq. (2) by \( \pi'_{re} \), we obtain

\[
\chi = \frac{\pi'_r}{\pi'_{re}} \frac{\pi'_e}{\pi'_{me}} = \frac{\pi'_o}{\pi'_{re}} \frac{\pi'_e}{\pi'_{me}} = \chi_2 \chi_1. \tag{3}
\]

The subscript \( o \) refers to the vessel with obstacles and \( e \), to the empty vessel; the parameter \( \chi_2 = \pi'_{ro}/\pi'_{re} \) characterizes the action of the obstacles and \( \chi_1 = \pi'_{re}/\pi'_{me} \) takes into account the role of the factors which intensify combustion in the absence of obstacles. Relation (3) allows one to consider separately two ways of combustion intensification owing to the flame instability in empty vessels and also to flame deformation in vessels with obstacles. The nondependence of the turbulization factor \( \chi \) on the process scale, i.e., on the vessel dimension with complete geometrical similarity of the shapes of vessels and obstacles, must indicate the scale modeling of gas combustion in closed vessels with obstacles.

**EXPERIMENTAL TECHNIQUE**

Experiments were performed using homogeneous propane–air mixtures with 3, 4, and 6% propane in four spherical vessels with volumes of 3.2 · 10^{-3}, 0.01, 0.1, and 1.14 m³ for initial pressures of 0.1, 0.3, and 0.8 MPa and at room temperature.

As obstacles, we used flat metallic perforated and solid disks. The disks were symmetric about the vertical axis and were mounted on metallic rods, whose length was varied. The geometrical dimensions of obstacles for various vessels were varied in proportion to the vessel diameter. The obstacle shapes and