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Improvable method of fire suppressant concentration measurement: An experimental validation

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ABSTRACT

An improvable method which could be used in fire suppressant concentration measurement is presented in this paper. The essential principle of the design is based on the Hagen–Poiseuille law. Gas mixture flow was driven to pass through a set of capillary tubes and pressure drop between ends of the tubes is measured. The pressure drop is a function of gas viscosity and the viscosity of binary gas mixture is actually determined by volume percentage of each component. Relationship between volume percentage and pressure drop can then be established. Results of experiments verify the theoretical analysis and show potential application prospect.

1. Introduction

The measurement of the distribution, dispersion and evaporation characteristics of a suppression agent is essential for characterizing the fire extinguishment process and certifying reliability of a fire-suppression system [1]. To ascertain the characteristic of an agent's distribution behavior after being discharged from the fire protecting system, it is necessary to seek an appropriate way to measure the accurate and real-time concentration of fire suppressant. For another aspect, new agents are developed to meet growing demands for fire suppressant. This also calls for necessary quantitative measurement methods in order to certify whether these new agents fulfill their design objectives or not [2–4]. Moreover, real-time suppressant concentration measurement methods could also be used in the design of distribution systems and to provide technical support in the certification of new gas fire protecting systems.

In the field of evaluation of fire suppression systems in aircraft engine compartments, for example, practical way to quantify the firefighting efficiency was required. Currently, the safety level for engine compartment fire protection is defined as an amount of Halon 1301 producing the minimum of a 6% volumetric concentration throughout the protected zone for a duration of one-half second. The premium is placed on the achievement of extinguishing concentrations which can be maintained for a period of time following extinguishment to prevent relighting on heated surfaces. This process has involved the evaluation of many chemicals and associated technologies. Better understanding of the diffusion behavior of the suppressants in the compartment, better methods of nacelle suppression could be presented and improved. Earlier work in the span of time concerned was based on actual fire testing. Results were quantified by agent weight and compared against fire extinguishment performance. These methods, however, were costly and ineffective. Generally, to examine the ability of agent to put out a fire in an unknown environment, one of the most effective ways to quantify is to measure and record concentration, distribution and duration of the agent gas in the region of interest. With the development of technology of gas concentration capture and record, agent concentration-versus-time profiles illustrating distribution in the protected zone could be obtained in time. In this context, the emphasis involved finding a simpler, yet more effective, way to measure and record concentration of gaseous agents.

In order to determine the characteristic of an agent's dispersion behavior, which is the most important in determining extinguishment efficiency, it is necessary to have the means to make accurate concentration measurements on the time scales of interest. To those agents incorporated into fire-extinguishment systems which came out newly, it will also be necessary to make quantitative measurements in order to certify that the new systems are meeting their design goal. Development of the capability of making the necessary concentration measurements for the design of dispersion systems and the certification of new systems, in brief, is the focus of this effort.

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Many systems used in agent gas concentration measurement were designed and constructed based on different physical or chemical fundamental principles. Researchers have developed many different kinds of devices which can be used in gas concentration measurement. For example, Yamazaki designed a gas concentration system with a venturi flowmeter and a laminar flowmeter [5]. And it showed good performance in measuring concentration of binary gas mixtures consisting of air and carbon dioxide or helium.

Another measuring method was based on infrared absorption characteristics of gases. When infrared light of specific wavelength passes through mixture of several gases, the specific gas will absorb a certain amount of the infrared light. Then the amount of the outgoing light is measured and the residual processed. Concentration then can be derived from the amount of infrared loss [6]. This method needs to measure the heat loss or conduction with application of different sensors. That is to say, sensors always play an important part in the field of gas concentration measurement. Indeed, development of sensors has greatly improved the measuring accuracy. Gas pressure or pressure drop sensors which were designed based on different principles of course were developed [7]. A typical example of infrared absorption improvement was the Differential Infrared Rapid Agent Concentration Sensor (DIRRACS) build by the National Institute of Standards and Technology (NIST). It was calibrated and tested with HFC-125 [8]. Another gas concentration measurement system was built from the patent of Yanikoski [9]. The typical model was Halonyzer, which was manufactured by Pacific Scientific [10]. They improved the Statham analyzer, which was actually the predecessor of Halonyzer and put it into use in concentration measurement of Halon 1301.

There are also many other measurement methods based on different or similar theories. Hot-film anemometers are most commonly used in velocity measurements. But several groups had developed probes which were capable of measuring concentration and velocity simultaneously by using two probes with very different responses [11,12]. However, the characteristic of the sensitivity and accuracy of this technique was not satisfactory. In 1992, Brown and Destefano developed the Fire Extinguishing Agent Sensor (FEAS) to provide a fast time response instrument capable of detecting the presence of an agent [13]. Similar to DIRRACS, this design was based on a technique of infrared absorption. Test results showed that response of the equipment was not perfectly flat and even a slight deviation could be significant. Another problem was its calibration of the device, which would require changing both the concentration and the rate at which the concentration was changed. As a result, it did not meet the requirements of accuracy and time response needed for a satisfactory instrument for monitoring the agent concentration. In 1993, an optical speckle technique was utilized by Oberste Lehn and Merzkirch for the indirect measurement of density fluctuations which could then be related to temperature fluctuations by assuming a constant pressure, ideal-gas flow. This technique allowed the entire flow to be analyzed simultaneously. However, it was also not appropriate for the current application since it required significant optical access and a very high degree of experiment sophistication. It would be difficult to record data in practical use.

In order to find a practical way in fire agent concentration measurement, this paper discusses an improvable method. The basic principle presented in this paper is similar to that of the Statham analyzer. Tests results showed its capability of measuring concentration of CO_2 in mixture of CO_2 and N_2 to be practical. Unlike the Statham analyzer, the concentration of fire suppressant agent was not calculated first from relative concentration and then converted into volumetric concentration with a calibration curve. Relationship between pressure drop which was expressed with voltage signal and the volumetric concentration of CO_2 in the mixture was obtained by the calibration procedure first. This result was then regarded as the standard curve. And data was stored in the computer. When carrying out a practical application, the voltage signal of pressure drop was measured, recorded and converted actually. By applying the standard curve to the data measured, the concentration could be obtained. Acquiring and processing of the data with a computer made the measurement procedure convenient and efficient. Test results were also obtained much faster and easier. This made it more timesaving to evaluate fire suppression systems.

2. Theoretical analysis

2.1. Hagen–Poiseuille equation

In fluid dynamics, the Hagen–Poiseuille equation is a physical law that describes the pressure drop in a fluid flowing through a long cylindrical pipe. The assumptions of the equation are that the flow is laminar viscous and incompressible; the flow is passing through a tube with a constant circular cross-section; its length is much longer than its diameter. In standard fluid dynamics notation, it can be written as

$$\Delta P = \frac{8\mu L Q}{\pi r^4} \tag{1}$$

where ΔP is the pressure drop between the ends of cylindrical pipes; L is the length of the pipe; μ is the dynamic viscosity; Q is the volumetric rate of flow of the gas; r is the radius of pipe cross area; and π is the mathematical constant.

Then, with all other conditions established, ΔP is only the function of the dynamic viscosity of fluid. And the relationship between them is linear. Then Eq. (1) can be rewritten as

$$\Delta P = k\mu \tag{2}$$

where k is the instrument coefficient determined by measurement system itself. This indicates that the pressure drop between the ends of the capillary tube can be expressed with viscosity of mixture of gases and the instrument constant coefficient.

2.2. Viscosity relationship of binary gas mixture

In general, viscosity of gas was obtained from experimental tests. When it was not convenient to conduct experiment or lack of database, it could be calculated with expressions as follows:

$$\mu_{mix} = \frac{\sum y_i \, \mu_i \, M_i^{1/2}}{\sum y_i \, M_i^{1/2}} \tag{3}$$

where μ_{mix} is the viscosity of gas mixture; y_i is the mole fraction of the ith element; μ_i is the viscosity of the ith element; and M_i is the molecular weight of the ith element.

2.3. Calculation result

The absolute viscosity of many fluids relatively does not change with the pressure but very sensitive to temperature. In fact, viscosity of gases varies widely with temperature. In gases, molecules are spare and cohesion is negligible. Thus, in gases, the exchange of momentum between layers was brought as a result of molecular movement normal to the general direction of flow, and it resists the flow. The molecular activity is known to increase with temperature, thus, the viscosity of gases will increase with temperature. The reason is a result of the consideration of the