

SFPE Classic Paper Review: Fire-induced Flow Through an Opening by Joseph Prah1 and Howard W. Emmons

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This paper reviews the classic work of Howard Emmons with Joe Prah1 [1] on vent flows in compartment fires. Among the many papers by Howard Emmons that could have been selected for a Classic Paper Review, this paper stands out because of its critical role in fire modeling and because it shows Emmons' scientific talents and engineering mindset at work. Within the combustion community, Emmons' paper [2] on laminar burning of a flat plate is a classic. Since he is most widely known as the father of fire modeling, many would assume that a Harvard Fire Code paper would be the subject of a classic review (e.g., [3]). Given his broad vision of fire as a scientific system, one of his review papers showing the richness and interconnected scientific problems in fire (e.g., [4]) or a paper on the history of fire science [5] could also be regarded as a classic. However, Prah1 and Emmons [1] has been chosen instead because it is an enduring work that stands today as a model of how fire research should be performed.

At the time the paper was written, the flow of gases in fully developed fires had already been studied by Kawagoe [6] (see review in [7]), who recognized the role of $A\sqrt{H}$. However, Emmons saw that treating a compartment as a well-stirred volume had its limitations in the early growth stage of the fire when the fire environment was highly stratified in what is now called a two-layer system. He recognized the similarities of flow out the door with the hydraulic problem of flow over a weir, a well-studied and understood fluid mechanics problem. He observed that when the layer depth was a small fraction of the opening height, the physics of the two problems



Professor Howard W. Emmons

were very similar. So, seeing model problems that described the two extremes of compartment vent flows (very shallow and very deep hot gas layers), Emmons set about to develop a mathematical model that treated the full range of conditions and matched the known limiting solutions. The results are the underlying basis for vent flow modeling in all zone models today.

It was no accident that Emmons chose to attack this problem. The Home Fire Project (led by Emmons at Harvard University, in cooperation with Factory Mutual Research Corporation (FMRC)-now FM Global Research) was begun in 1972 with the goal of understanding compartment fire growth and the development of hazardous conditions responsible for fire injuries and deaths in the home. The first internal report [8] for the Home Fire Project in 1974 was Emmons' development of the basis of the model later included in this paper. In the first few years of the Home Fire Project, three full-scale, well-instrumented bedroom fire tests were performed jointly with FMRC. Emmons' goal in conducting these groundbreaking experiments was to define critical phenomena required to understand the overall fire development. The objective was to identify critical phenomena and to study them as scientific problems. Ultimately, the reconstruction of these component phenomena into a complete system is the zone fire model as we know it today. Emmons recognized that the flow of air into the compartment and venting of products of combustion are critical to the understanding of compartment fires.

Emmons' vent model clearly identified the roles of the hot layer interface and the vent neutral plane. While the hydrostatic pressure difference variations about the neutral plane were used as the driving force in the

model, the modern reader will be surprised by the absence of the typical plot of pressure difference variations with height that are included in handbook or textbook developments of the theory (e.g., [9,10]). The model takes the interface height and layer densities as known and uses the hydraulic flow equations with conservation of mass to define the location of the neutral plane and the flows into and out of the compartment. The mass contribution from the fire source was included in the development. While Prah1 and Emmons understood the role of plumes in feeding the layer, this coupling is not explored in the paper. They had recognized the vent flow problem as a component of any fire model that needed to be modeled and understood, and in this paper focused directly on this well-defined problem. Rockett [11] used Emmons work in this area and specifically dealt with the interaction of vent flows and plume flows. Rockett's paper is well worth reading.

The development of the vent model was presented economically with significant space being used to explore the model and present insights derived from the model. Beyond showing that their model matched the results of Kawagoe under choked flow conditions, Prah1 and Emmons also observed that the flow rate through the vent was relatively insensitive to layer interface height when the layer interface was in the lower half of the vent. This shows why $A\sqrt{H}$ is so valuable for correlating preflashover data such as the MQH correlation [12].

While Emmons conceived the project and had developed the basis for the model, the experimental work was developed and carried out by Prah1. Joe Prah1 completed his PhD under Emmons at Harvard in 1968. Subsequently, he took a faculty position at Case Western Reserve University and had returned to Harvard during a sabbatical in 1974 to participate in this vent study. He is currently the chair of the Department of Mechanical and Aerospace Engineering at Case and has been an active researcher with NASA, including a role as the Backup Payload Specialist for the United States Microgravity Laboratory, which flew in June 1992.

Professor Emmons earned his PhD at Harvard in 1938 and returned to Harvard as a Professor in 1940. His interest in fire as a scientific problem dates from the 1950s through work with Hottel and the National Academy of Science [13]. Hottel reviewed the emergence of fire science in these early days in a symposium honoring Emmons upon his retirement from Harvard in 1983 [14]. Emmons was instrumental in the formation and funding of the Center for Fire Research at the National Bureau of Standards (now NIST Building and Fire Research Laboratory) around 1970. Emmons continued to be a driving force and visionary in fire research until his death in 1998.

Prah1 and Emmons recognized that, like the hydraulic models that motivated their work, there was a need for a single empirical constant for

the model, the discharge coefficient. After developing the theory, the paper reports several sets of preliminary experiments used to study the problem. The paper described the use of a 1/4 scale gas-fired compartment fire experiment by Tom Shen in Emmons' laboratory to measure doorway velocity profiles and to determine discharge coefficients. Saltwater modeling experiments were also used to deduce discharge coefficients, as well as water flow weir experiments reported in the preliminary work section of the paper. Some investigators would have published three papers out of what Prah and Emmons regarded as preliminary work, taking up only a small section of one paper. This small section is followed by the primary experimental section.

The primary experimental work was small-scale kerosene/water experiments, using a modified setup of an existing test facility at Harvard. As an undergraduate and graduate student at Harvard, Prah was very familiar with the facilities and was able to adapt the existing apparatus to this problem. Kerosene was used as the lighter "hot" fluid and water as the heavier "cold" fluid. Since the liquids are immiscible, there was no question of mixing affecting the layer densities, no ambiguity in defining the interface, and no difficulty in recovering the original fluids so that the experiment could continue indefinitely to allow close examination of the flow. Orifice meters were used to measure fluid supply rates to within 2%. Layer and neutral plane heights were measured with a cathetometer to an accuracy of less than 0.1 mm in openings with heights of 50 and 125 mm. These experiments were performed with a precision that is unthinkable in an actual fire experiment. The measurements validated the model and resulted in Prah and Emmons recommending an average discharge coefficient of 0.68. Measured inflow coefficients were generally somewhat less and outflow coefficients somewhat higher. Of course in doing small scale testing, Emmons and Prah were cognizant of scale effects and used the high Reynolds Number results as the basis for recommended constants for use in large-scale fire applications.

The work is a *tour de force* in applying a wide range of modeling methods to a fire problem; mathematical, gas phase scale modeling, saltwater modeling, and water/kerosene modeling. While there were detailed velocity and temperature measurements in the door flows in the full-scale Home Fire Project, Emmons never did full-scale fire experiments suitable to validate his model. This was achieved years later [15]. That work concluded that the best discharge coefficient for inflow was 0.68 and for outflow was 0.73. Averaging these results in a discharge coefficient of 0.70, just slightly higher than Prah and Emmons 0.68. Subsequent Japanese work referenced by Steckler et al. [15] (in response to questions) gave a recommended discharge coefficient of 0.68.

The science described in this paper is now thirty years old. The model is the basis for vent flow calculations in zone models today and the model constant determined by Prah1 and Emmons has been further validated and continues to be used.

It is interesting to relate this paper to Alpert's recent review [16] of Hottel's classic paper on pool burning. Alpert noted that Hottel regularly pointed out to those relatively new to fire research when similar work had been done years before. Emmons and Hottel were friends from the 1950s through the rest of their lives. A footnote on the first page of Prah1 and Emmons [1] read, "After completion of this work, Hoyt Hottel pointed out that many of the ideas used in this paper appeared in the work of Yesmann (in French in 1910) and were printed in English in the furnace design book by Groume-Grjmailo (in 1921)". The footnote is true to form for both Hottel and Emmons, Hottel for the comment and Emmons for acknowledging it in print. Indeed, the roots of work done today are found often in the distant past in a related field of research. We all stand on the shoulders of giants and Howard Emmons is one of them.

Editor's Note:

I had several discussions with Howard Emmons before starting work on an analytic solution for the fire-induced ceiling jet. Emmons emphasized that such a solution was possible and suggested assumptions that could be made to make the problem tractable. These discussions gave me the confidence to proceed and eventually complete the work. It was Emmon's positive attitude and confidence building that inspired many fire research projects at FM Global Research and at numerous other institutions.

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