Interaction between Two Burning Vertical Walls

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ABSTRACT

A study was conducted on the structure of the turbulent reacting flow developed between two burning vertical walls. Large-scale, gas-supplied, water-cooled, sintered-metal burners facing each other were used for the experiments. We examined the influence of different parameters such as channel width, burner, length, gas supplied, flow rate and mass transfer driving force B..., on the establishment of a steady turbulent fire. The flow field (velocity and turbulence) was characterized through a statistical analysis of LDV measurements. Mean and fluctuating temperature profiles were also obtained with a similar analysis. The results indicate that, as the distance between both walls decreases, radiation is no longer the dominant mode of heat transfer. The character of the flow changes from natural to forced convection, and there is a "relaminarization" of the flow.

INTRODUCTION

The study described in this paper was undertaken primarily to investigate the effect of spacing on the steady rate of burning of intermediate-scale, vertical, parallel walls. As in a previous work done at Factory Mutual (1), this research on the burning of parallel walls was aimed at providing new experimental information on a problem of practical interest. The situations to consider range from the development of fire through shelves rows where combustible materials are stored, to bundles of electric cables for electronic or electric equipment, rack stored....

Prior to this work, our laboratory has been involved for several years with the modeling of a compartment fire. One of the points which must be studied turns out to be the combustion and the propagation along a burning wall. In earlier theoretical studies (2, 3) the flow along the combustion zone is assumed to be laminar. The turbulence induced by the phenomena was introduced later on in other models. The studies of references (4, 5) which include a turbulence model and a probabilistic combustion approach, gave noteworthy results but required too long a computing time. For that reason other authors attempted to simplify this approach. The classical integral method used in (6) was improved after modification in (7) considering mean and fluctuating velocity and temperature measurements (8). Simultaneously we started a very similar work in our laboratory. Two different experimental approaches have been tested (9, 10). In the first one, we determined the structure of the flow along the burning surface of a Pmma slab and above it in the propagation zone. In the second case, we explored the

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boundary layer developing along a stack of porous wall burners. As the results obtained are very similar to those presented in (8) we considered our burners as very reliable and decided to use them to characterize some typical situations encountered during the spreading of fire and especially the interaction between vertical walls. In this work, however we principally focused our attention on the effect of the problem parameters on the structure of the flow.

EXPERIMENTAL SETUP

Test Facility

The experimental set-up consists of two vertical, parallel walls, capable of sustaining fuel burning, and the instrumentation required to characterize the wall burning process. Vertical walls are constructed by means of modular burners 0.4m wide by 0.25m or 0.5m high stacked one on top of the other to achieve the desired height from 0.25m to 1.25m. These burners are water-cooled, gas-supplied, sintered metal units, very similar to the ones previously used at Factory Mutual (8, 11, 13). A schematic view of a burner unit and of the burner assembly is shown in Fig. 1. Measured rates of fuel gases are supplied to the gas plenum, one wall of which is a water-cooling coil embedded in aluminium powder and sandwiched between two 0.005m thick rectangular sintered-stainless steel slabs. Two 0.5m deep water-cooled side-walls prevent three-dimensionnal lateral air entrainment without restricting normal fuel-air mixing. The side-walls are water-cooled to prevent extra-radiation transfer to the burner surface and insulated from them to avoid conductive heat transfer. The back and the sides of the gas plenum are also insulated to minimize any heat losses from the burners to the ambient. The heat feedback to each burner, q", is obtained by differential thermocouple measurements of the entrance and exit cooling water temperatures and the measured water flow rate. The fuel flow rate through each burner, m", is individually controlled by a flowmeter and a valve. As it has been shown earlier (11) solid and liquid fuels, characterized by their mass transfer number B, can be simulated by controlling the effective heat of vaporization L = q"/m". In the present work predetermined B numbers related to m" ranging from 1 to 5 g/m.m/s were maintained for each burner by adjusting its fuel supplied rate. Technical grade propane was the fuel used for all tests.

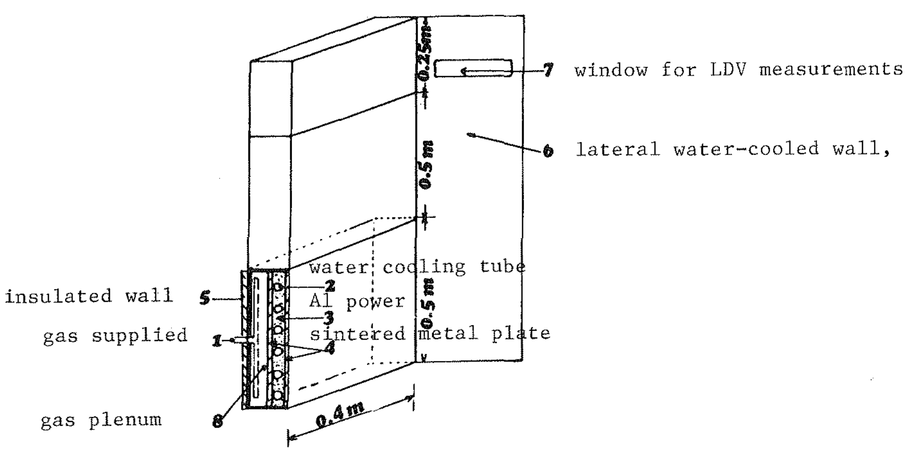


FIGURE 1. Burner Assembly.

Instrumentation

Velocities were measured by a 1D laser doppler velocimeter. The frequency spectrum was monitored by a spectrum analyser and the doppler signal was processed by a velocimeter counter. The ambient air was seeded at the bottom of the wall, using a pressurized cyclone container, with particles of zirconium oxide (1 to 3 μm in diameter) required for the LDV measurements. The penetration rate, n°, of the particles into the velocimeter measurement volume changes not only with the location in the reacting stream but also with the local aerodynamic and thermodynamic properties of the flow. If n° is closely related to the properties of the environment, the measured mean velocity, Up, will be different from the real fluid mean velocity $\overline{U}$. Using different assumptions for n° based on previous works (8, 14, 15, 16, 17, 18) and carrying out extra measurements we estimated the correlation $\overline{n^\circ U}$.

A chromel-alumel thermocouple (wires 50 μm in diameter), positioned a few mm downstream of the laser measuring-volume to avoid disturbance of the flow, gives a signal proportional to the instantaneous gas temperature. Temperature data analysis takes into account time constant compensation and radiative heat losses (numerical compensation) (14, 18, 19). For each doppler signal validated by the LDV counter we execute a measurement of the gas temperature T and of the time interval Δt between two validated doppler signals. Three sets of 512 data simultaneous measurements are stored on a disk, in addition three other sets of 1024 gas temperature measurements at a frequency of 500 Hz are also stored. Various statistical means are calculated for the mean time and temperature. The sensitivity of the statistical analysis is studied by relating the penetration rate to either the local temperature, or the crossing time of the particle through the measuring volume, or the time interval between two validated signals.

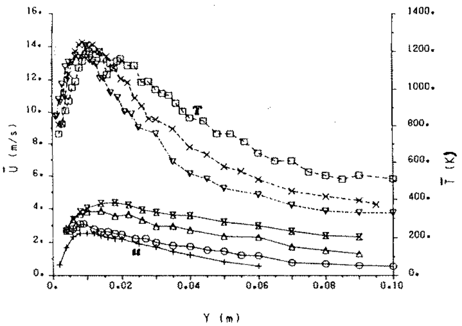
EXPERIMENTAL RESULTS

Single wall results

To test the reliability of the experimental setup we first made experiments in conditions very similar to those prevailing during the tests carried out at Factory Mutual (8) and compared the results from both tests. As it was shown in reference (10) the agreement between the two sets of data is quite good. The data obtained along a wall alone will serve as a reference basis to underline the influence of a second wall, burning or not burning, of the same height but located at different spacing lengths. All velocity, turbulence and temperature measurements are made at three (0.4, 0.9, 1.15m) or four (0.65m) different locations x from the leading edge of the burner. The measured mean velocity and temperature profiles are illustrated in Fig. 2. Figure 3 illustrates the mean velocity data plotted in the coordinates $(\overline{U}.x/\nu_\infty)Gr^{-1/2}$ and $(y/x)Gr^{1/10}$ as suggested in paper (13). Similarity of the boundary layer thickness in these coordinates is very clearly indicated in the figure, but the scaling is not very good. Figure 4 shows unambigously the very small influence of fuel blowing rate, m'', on the flow characteristics.

Results for two walls with only one burning

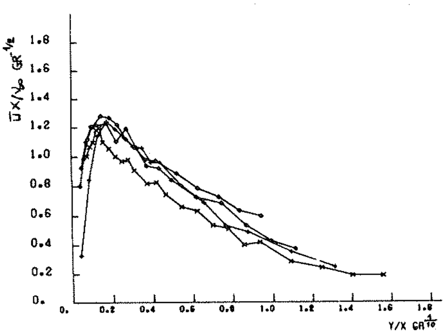
To show the influence of the second wall on the structure of the reacting



U : + x = 0.4 m
0 x = 0.65 m
Δ x = 0.9 m
Ⴟ x = 1.15 m

T : ∇ x = 0.4 m
X x = 0.9 m
□ x = 1.15 m

FIGURE 2. Cross-Stream Velocity and Temperature Profiles at Different x Along an Alone Vertical Burning Wall. m" = 0.003 kg/m.m.s



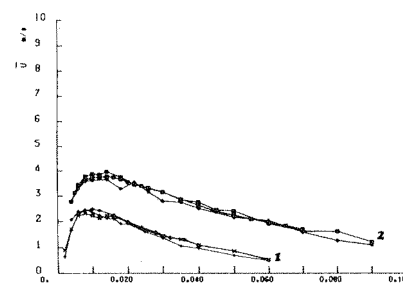
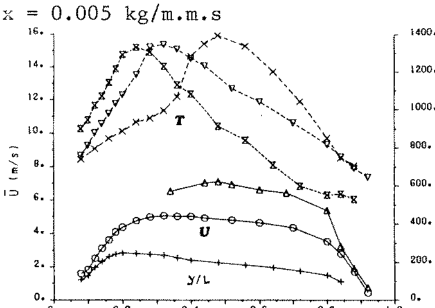


FIGURE 3. Velocity Profiles (same data as in Figure 2) in Coordinate Provided by the Analysis of Reference 13.
U : X x = 0.4 m, + x = 0.65 m ◇x = 0.9 m ■x = 1.15 m

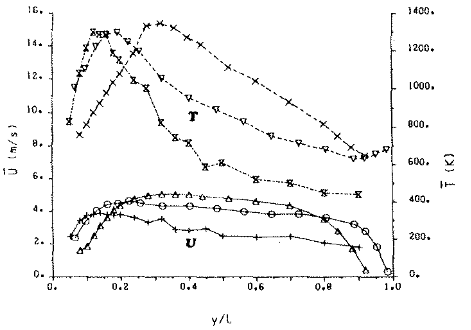
FIGURE 4. Influence of Mass Fuel Flow Rate, m", on Velocity Profiles, a Burning Wall Alone.
1) x = 0.4 m + x = 0.003 kg/m.m.s X x = 0.004 kg/m.m.s◆ x = 0.005 kg/m.m.s
2) x = 0.9 m ◆x = 0.003 kg/m.m.s □x = 0.004 kg/m.m.s◇ x = 0.005 kg/m.m.s



U : + x = 0.4 m
0 x = 0.9 m
Δ x = 1.15 m

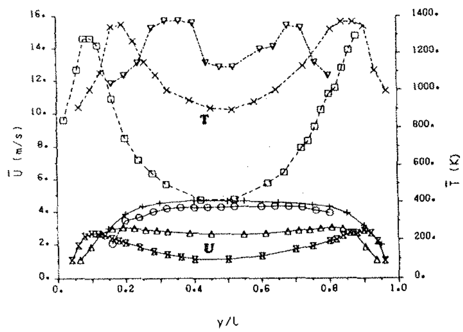
T : Ⴟ x = 0.4 m
∇ x = 0.9 m
X x = 1.15 m

FIGURE 5. Two Vertical Walls, one in Combustion, l = 0.05 m Velocity and Temperature Profiles. m" = 0.003 kg/m.m.s



1) l = 0.05 m Δ U ; X T ;
2) l = 0.06 m O U ; ∇ T ;
3) l = 0.10 m + U ; ⧖ T .

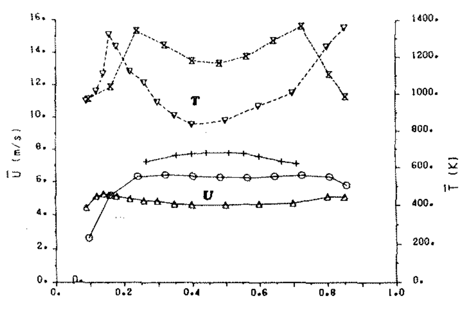
FIGURE 6. Two Vertical Walls, one in Combustion, x = 0.9 m. Velocity and Temperature Profiles as a Function of (Y/l)



A) x = 0.4 m :

⧖ l = 0.10 m, Δ l = 0.062 m,
O l = 0.05 m, + l = 0.04 m
for U.
□ l = 0.10 m, + l = 0.062 m
∇ l = 0.05 m,
for T.

FIGURE 7A. Two Vertical Burning Walls, m'' = 0.003 kg/m.m.s. Velocity and Temperature Profiles.



B) x = 0.9 m :
Δ l = 0.10 m, O l = 0.062 m,
+ l = 0.045 m,
for U.
∇ l = 0.10 m, ⧖ l = 0.062 m
for T.

FIGURE 7B. Two Vertical Burning Walls, m'' = 0.003 kg/m.m.s. Velocity and Temperature Profiles.

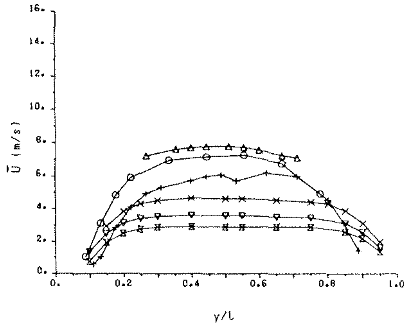
flow we plotted the data $\overline{U}$ and $\overline{T}$ as a function of y/l at different x. In Fig. 5 and 6 the influence of the confinement appears clearly when x increases, especially at smaller l. The maximum of velocity and temperature moves toward the center of the channel (y = l/2) as x rises, a phenomenon that is enhanced by decreasing l. By moving the inert wall closer to the flame, we observe the transition from a purely natural convection flow to a mixed and then to a forced convection stream whose development length is also related to l (wall spacing).

Results for Two Vertical Burning Walls

Figures 7A and 7B, where $\overline{U}$ and $\overline{T}$ profiles are plotted as a function of y/l at different x for several l, express clearly the influence of the second reacting wall on flow acceleration, development length and crossflow mean temperature. There is of course no dissymmetry in the profile shapes (same channel boundaries) but all the trends observed above are greatly enhanced by the increase in heat released. As l becomes smaller we observe again the flow transition but only between mixed and forced flow and a decreasing in the entrance or establishment length. These profiles also show that for a fully developed flow the mean temperature is very similar to the temperature measured in the flame zone. After some distance, except for the near wall zone, the channel is filled by only one flame corresponding to a plateau for $\overline{U}$. For $\overline{T}$ it is a little different. The cross flow profiles are never completely flat and present a shallow minimum at the center. This phenomenon can be related to non unity Prandtl number and to the flow acceleration due to the confinement. All these observations remain valid for different m'', but as shown in Fig. 8 with a significant influence of m'' on $\overline{U}$, not observed in the pure natural convection case. The increase of the magnitude of the property at the plateau being caused by the increase in the heat released and consequently in overall flow rate. The difference observed becomes meaningful only at low l for U, but not really for $\overline{T}$ because of the lack of fresh air entrainment at center line.

DISCUSSION

As a first step we tried to explain the above results. They are perfectly summarized by the graphs plotted in Fig. 9A and 9B where l = 0.10m. The $\overline{U}$ and $\overline{T}$ profiles confirm the visual observations and especially the transition from a pure natural convection flow to a forced flow. For a given wall spacing the flow appears fully developed before the end of the channel. This is true for the velocity, but occurs only for the temperature at narrower l. The "relaminarization" of the flow is evident after looking at the data plotted in Fig. 10. Effectively the turbulent intensity $(\overline{U'^2})^{1/2}/\overline{U}$ decreases drastically by reducing wall spacing and also by increasing the flow acceleration (small l and two surfaces in combustion). This intensity drops from nearly 30% for pure natural convection to 5 % when the walls burn with a wall spacing close to 0.04m. For temperature, Fig. 11, the phenomena are less significant, the average value of $(\overline{T'^2})^{1/2}/\overline{T}$ being always very closed to 5 - 10% regardless of the case considered.



x = 0.4m

1) m" = 0.00115 kg/m.m.s X

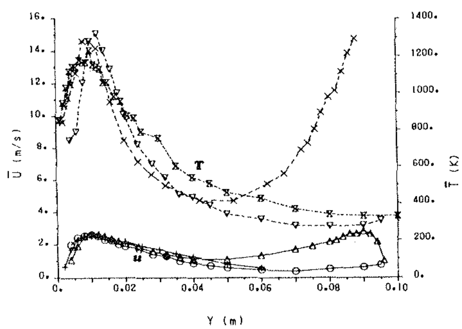
2) m" = 0.0015 kg/m.m.s ∇

3) m" = 0.003 kg/m.m.s X

x = 0.9m

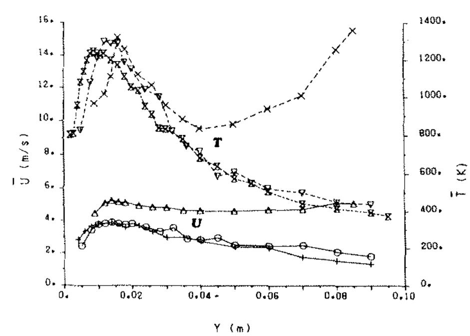
+, 0, Δ,
same m" as for x = 0.4m

FIGURE 8. Two Vertical Burning Walls, l = 0.04m. Influence of Mass Flow Rate on Velocity Profiles.



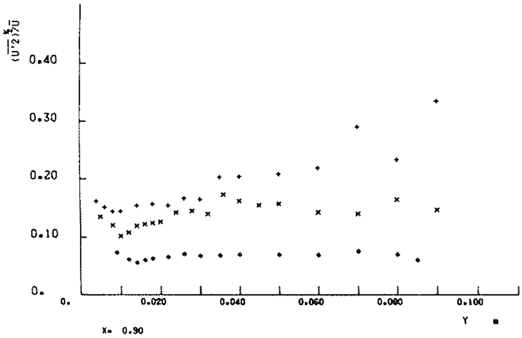
9A) x = 0.4m
Velocity : + x one burning wall only,
0 one burning and one non burning wall at l = 0.10m,
Δ two burning walls at l = 0.10m ;
Temperature : ∇ one burning wall alone
X one burning and one non burning,
X two burning walls.

FIGURE 9A AND FIGURE 9B. Velocity and Temperature Profiles in the Three Cases Studied.
m" = 0.003 kg/m.m.s, channel height 1.25m.



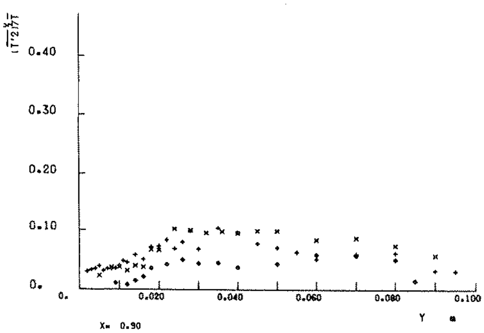
9 B) x = 0.9m

same symbols and conditions as for x = 0.4m



x = 0.9m
1 = 0.10m
+ only one wall burning
X one burning and one non burning wall
◆ two walls burning

FIGURE 10. Velocity Turbulent Intensity Profiles : m'' = 0.003 kg/m.m.s.



x = 0.9m
1 = 0.10m
+ only one wall burning
X one burning and one non burning wall
◆ two walls burning

FIGURE 11. Temperature Turbulent Intensity Profiles : m'' = 0.003 kg/m.m.s.

CONCLUSION

In this work we studied experimentally the aerodynamic and thermal structure of the flow developing between two vertical burning walls. The different measurements show how the transition from a pure natural convective flow to a fully developed forced flow occurs as a function of various parameters characteristics of the problem. The distance from the leading edge, x, but mainly the acceleration of the flow due to the confinement (channel spacing length l) and the thermal expansion of the burning gases (one or two wall in combustion), play an important role on the transition and also on the "relaminarization" of the reacting stream. We also observed that the influence of the injected mass flow rate, m'', nearly unimportant for an unconfined natural convective flow becomes more and more significant as the stream becomes more confined. Under confinement conditions we can assume, that the dominant heat transfer mode is no longer radiation but the forced convective one, as previously observed in an other configuration (14, 15, 18). An analytical and a numerical approach will be proposed in the near futur in order to correlate these results with the characteristic parameters defined above.

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