

AN EXPERIMENTAL STUDY OF WIND FORCE ACTING ON COMMERCIAL DOUBLE-LAYERED SQUARE METAL SCREENS AT DIFFERENT SPACING

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Abstract

In this study, an experimental setup was established to measure the pressure drop of flow through single- and double-layer woven metal screens. Three woven metal screens with different porosities of the plain-square type were tested in this study. The Reynolds number based on the screen wire diameter ranged from $Re = 111$ to $Re = 2890$ and the range of porosity was 0.34 to 0.67. Based on the measured drag coefficient of the three single- and double-layer plain woven metal screens, this study indicates the drag coefficient of low porosity double-layer screen is less than twice of that of the single-layer screen if the spacing of two layers remains less than 14 times of the screen wire diameter.

Introduction

A previous study identified ember attack as the predominant bushfire attack mechanism [4]. They also found that wind born debris causes more than 90% of house fires in urban areas during bushfire. The Australian Standard for construction of buildings in bushfire-prone areas (AS 3959-1999) recommends that all openable windows and external doors should be screened with screen with a maximum aperture size of 1.8 mm [13]. However, recent study indicates firebrands penetrate through a single screen and they are not quenched and would continue to burn until they are able to fit through the screen opening [8]. It is conceived that a double-layer metal screen with smaller openings might be able to block a higher percentage of firebrand flux. In addition to the problem of ember attack, there are three further problems associated with the use of single-layer screens.

In the work of Sharifian and Buttsworth [9] it was shown that a single-layer screen is capable of blocking a high percentage of radiation directly from the fire when a low porosity screen is used. However, radiation from the hot screen limits the application of single-layer screens to situations in which a wide buffer zone (the distance between the screen and the object(s) being protected from the fire) exists already [9]. One potential strategy to reduce the significance of radiation heat flux from hot screens (indirect radiant heat flux) is the use of a double-layer screen as the radiation barrier. A double-layer screen radiation barrier is expected to diminish the effects of both direct [10] and indirect radiation heat flux. Indirect radiation heat flux depends primarily on the temperature of the second layer (the layer closest to the object being protected from the bush fire) which in turns is related to the spacing between two screens, the screen material (particularly its emissivity), the wind speed, the duration of bushfire and its size. It is reasonable to assume that even in the worst conditions where the first screen is in contact with fire and approaches the fire's temperature, the temperature of the second screen will be somewhat less than the fire temperature. As the radiation heat flux scales with T^4 , a modest drop in temperature below the fire temperature can significantly decrease the indirect radiation heat flux.

The second problem associated with using a single-layer screen is existence of hot spots. If the screen is close to the object during bushfire, points at the centre of the object which are not protected

by the screen will experience a total radiant heat flux that is actually greater than in the case where no screen is used. To eliminate the hot spots, the object should have a minimum standoff distance from screen which is dependent on the screen cell size and is of the order of few millimeters for screens with an aperture of less than 1.8 mm [11].

The third problem arises due to high wind forces when a low porosity screen is used. Experimental work (Ehrhardt, cited in [2]) and computational work [12] show that the wind force is related to the screen porosity. High wind forces will occur for large scale screen deployments and this is problematic. For example, high mechanical stress within the screen may occur due to the wind loading and the screen may already be weakened due to elevated temperatures.

Using a double-layer screen has the potential to solve all of the above problems. A double-layer screen is proven to block a higher percentage of direct radiant heat flux [10]. Double-layer screens could conceivably reduce indirect radiation heat flux due to the lower temperature of the second screen layer. Minimization or elimination of hot spots should be possible with the correct spacing of the layers. Finally, it may be possible for a double-layer screen to have a lower drag force than a single-layer screen under some special circumstances [3]. The present study reports on a series of experiments conducted in order to determine wind force acting on some low-cost single- and double-layer square metal screens at different spacing.

Literature review

There is sufficient experimental and computational work regarding the drag force on the single-layer screens that are placed in a wind tunnel. According to those reports, the wind force (F_D) on a single-layer screen relates only to the screen porosity (p) and Reynolds number (Re) based on the screen wire diameter (d). Sharifian and Buttsworth [12] have presented the following computational equation for a single-layer screen with overall error estimated to be less than 14.5%;

$$C_d = -0.491 + \frac{0.47}{p^{1.773}} - \frac{7.49}{Re^{0.661}} + \frac{6.475}{p^{2.244} Re^{0.661}} \quad (1)$$

$$p = \left(1 - \frac{d}{L}\right)^2 \quad (2)$$

$$C_d = \frac{F_D}{\frac{1}{2} \rho V^2 A} = \frac{\Delta P}{\frac{1}{2} \rho V^2} \quad (3)$$

Where L is the screen cell size, ρ is the air density and C_d is the drag coefficient based on the mean wind speed (V).

According to [3], in some circumstances it is possible that the drag coefficient of the combined screens will be less than that of either of the individual screens. However, that author did not elaborate on the circumstances. This interesting point indicates that it is possible, by using a double-layer screen, the drag force can be even less than a corresponding single-layer screen. As



Figure 1. The cell size discrepancy of low-cost metal screen (reproduced from Ranjit 2008)

single-layer screen at higher porosity has lower drag force than lower porosity screen, it is expected that the drag force decrease considerably when a double-layer screen is used.

By way of explanation, it is possible that the parallel wires of two screens in tandem behave similarly to cylinders in close proximity in a tandem arrangement. Experimental and computational works on two circular wires show that the drag force on two wires in contact can be only 40% of the drag force on one wire alone [5,6]. Bokian & Geoola [1] show that two cylinders do not need to be exactly aligned behind each other to give a negative drag coefficient to the second cylinder. This is an important point as the cell size of the low-cost screens varies and cannot be aligned in tandem properly (see figure 1). The high quality screens which have identical cells are expensive and consequently the prospect to be used in bushfire applications as a fire barrier is slim. Their prices are of the order of several hundreds to few thousands Australian dollar per square metre.

Experimental setup

The wind tunnel used for this work is an open circuit subsonic wind tunnel (see figure 2). The air is sucked in through a honey comb structure followed by a fine wire screen to even the flow profile. According to the manufacturer's instruction, the velocity profile remains flat over 95% of the test-section. The test-section is a 305 mm x 305 mm square and made of high quality laminated fibre glass for better visibility. Convenient access to the interior of the test-section is provided through a lid at the top of the section. The wind tunnel includes a manometer to measure the pressure loss at two sides of the test-section. Two holes at the base of the test-section are connected to the manometer to measure the static pressure at two sides of the test specimen. A scale is attached to the manometer which is calibrated to read off the deflection as millimetres of water instead of the real gage fluid.

The wind tunnel also includes a Pitot tube to measure the wind speed. The Pitot tube is mounted at the centre of the test-section and connected to the manometer to measure total pressures. The air velocity is assumed to be uniform over cross section. However, based on previous experiments in the wind tunnel, this assumption may introduce an error up to 1% at the lowest velocity (4.5 m/s) which is ignored in this work.

The test-section does not have a facility to hold screens in place hence a piece of equipment which has been termed as "frame" was designed and manufactured (see figure 3). The outside dimensions of the frame are 305 mm x 305 mm and each wall of the frame is 40mm wide on the side and 15 mm thick. The space



Figure 2. The wind tunnel (adapted from Ranjit 2008)

between the screens could be altered using a number of spacers from zero to 25 mm wide.



Figure 3. The frame used to hold screens in the wind tunnel (reproduced from Ranjit 2008)

A barometer and a thermometer were used to monitor the atmospheric pressure and temperature during experiments and these measurements were used to calculate air density.

Metal screens come in different materials and are made with different techniques such as perforated metal screens (by punching holes in a thin sheet of metal), welded metal screens and wire woven screens. For this project low-cost, wire woven screens of square-cell and made of stainless steel were used. Double-layer screens are two similar single-screens with the best possible alignment behind each other in order to minimize the drag coefficient. Three metal screens which were being used had the following geometries (according to manufacturer's specification);

- $d=0.45$ mm, porosity= 34%,
- $d=1.60$ mm, porosity= 57%,
- $d=1.60$ mm, porosity= 67%,

The wind tunnel has an invariable square test-section and is positioned horizontally. In addition, the air flow is assumed to be incompressible. Based on the momentum equation, the wind force is equal to pressure loss multiplied by the projected area of the screen and thus the drag coefficient can be calculated using equation (3). In this work, the wind speeds and the pressure losses are measured by Pitot tube and two manometers at two sides of the test specimen, respectively.

Results

Single-Layer Screen experiments

In the first series of experiments, the relation between the drag coefficients of the single-layer screen versus Reynolds numbers was investigated and the results were compared to those obtained from the computational equation (equation (1)). In the first step, only the frame was placed in the wind tunnel and pressure losses and wind speeds were measured. In the second step, the experiments were repeated for three single-layer metal screens (porosity 0.34, 0.57, and 0.67). The measured pressure losses were corrected for the pressure losses measured at the same velocity in the first step. The calculated pressure losses were converted to C_d (equation (3)) and the velocities were converted to Reynolds numbers based on the screen wire diameter. The results are presented in figure (4). The experimental and computational results show good agreement. The drag coefficient decreases as the porosity and Reynolds number increases. The drag coefficient reaches to a flat value at high Reynolds number of about 2000 for the screen with porosities 0.57 and 0.67. For the screen with porosity 0.34, the maximum Reynolds number was 528 and C_d did not reach to a constant value. The maximum error is 26.6% at porosity 0.67 and $Re=622$. It should be noted that due to errors related to the manometer reading and slight fluctuations of the manometer, a higher relative error is expected

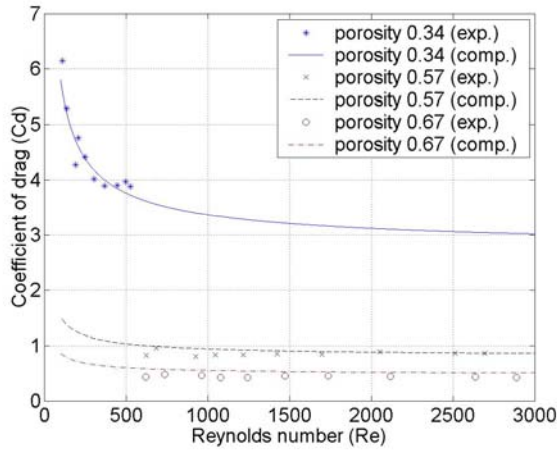


Figure 4. Comparison between ratios of measured C_d to computational C_d versus Reynolds numbers (Re) for three metal single-layer screens at porosities 0.34, 0.57, and 0.67.

at lower Reynolds numbers. The accuracy of reading was about 0.5 mm and the minimum deflection has been about 1.5 mm which suggests an error up to 33%. The error reduced as the pressure loss increased and reached to a minimum value of 1.04% (porosity=34% & Re= 528).

Double-layer screen experiments

In second series of experiments, three double-layer screens with porosities of 0.34, 0.57, and 0.67 were placed in the wind tunnel and pressure losses were measured in a similar way to previous experiments. For all screens, the spacing was increased from zero until further increase did not change the pressure loss. The maximum spacing was 8 mm, 10 mm, and 21 mm at porosities of 0.34, 0.57, and 0.67, respectively. The measured C_d was divided by the computational C_d (equation (1)) and the results are plotted in figure 5.

According to the results for the double-layer screen with porosity of 0.34, the C_d ratio at all s/d ratios shows variability at lower Reynolds numbers less than 300 (represents $V=10.99$ m/s) but reaches to a constant value at higher Reynolds numbers. By increasing the s/d ratio, the C_d ratio rises and reaches to 2.18 at $Re=394$ (represents $V=14.69$ m/s). It should also be noted that the maximum achievable Reynolds number reduces by increasing s/d ratio due to rise of pressure loss. The maximum Reynolds number reduces from 528 (single) to 394 ($s/d = 17.78$). It can be seen that the Reynolds number has minor effect on the C_d ratio.

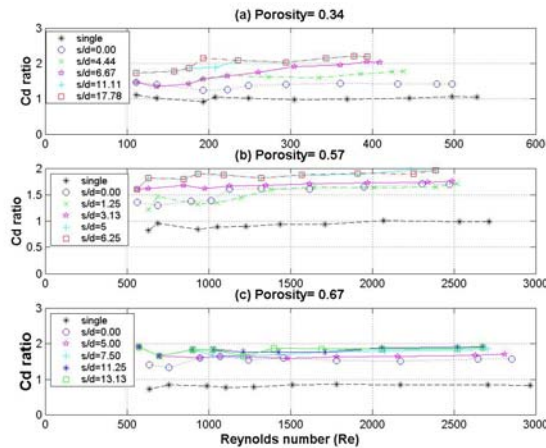


Figure 5. The ratio of experimental C_d to computational C_d versus Reynolds number at different spacing ratios (s/d) and at porosity of a) 0.34 b) 0.57, and c) 0.67.

Results for the double-layer screen with porosity of 0.57 are consistent with those observed in the previous experiment. The C_d ratio indicates fluctuation at Reynolds numbers less than 1300 (represents $V=11$ m/s), but reaches to a constant value at all s/d ratios. The maximum C_d ratio is 1.96 and occurs at $s/d = 6.25$. The maximum Reynolds number is 2716 (single-layer) and reduces to 2390 at $s/d = 6.25$. Reynolds number has relatively a minor effect on the C_d ratio, similar to the previous experiment.

For double-layer screen at porosity 0.67, the C_d ratio is high even at zero spacing (1.87). The ratio rises to about 2.22 at $s/d = 13.13$. Similar to the previous double-layer screens, the experiments indicate fluctuation in C_d ratio at Reynolds numbers less than 1300 (represents $V=11$ m/s). The maximum achievable Reynolds number also decreases from 2854 (single) to 2677 at $s/d = 13.13$.

Discussion

The results of all experiments show that there is a discrepancy in measured C_d ratios at lower Reynolds numbers or at velocities less than 11 m/s. It appears that the fluctuation is related to the velocity and not to the defined Reynolds number. The discrepancy at lower velocities could be caused by uncertainty in manometer reading (± 0.5 mm). Figure 5 shows the maximum fluctuation occurs at porosity= 0.34, $s/d=0$ and between $Re= 136$ and $Re=193$ where C_d ratios are 1.40 and 1.23 respectively. In the case of $Re=136$, the deflection is 8.5 mm and the estimated relative error due to the uncertainty of the manometer reading is 11.8% ($((0.5+0.5) / 8.5 \times 100)$). It should be noted that the manometer deflections in all experiments are subtracted by the corresponding deflection when single frame was used. As both readings could have 0.5 mm errors, the maximum reading error is estimated to be 1 mm ($0.5 \text{ mm} + 0.5 \text{ mm}$). The deflection is 14 mm at $Re= 193$ which represents a relative error of 7.1%. The C_d ratio discrepancy is 13.8% ($((1.40-1.23) / 1.23 \times 100)$ which equals the maximum estimated relative error ($(11.8^2 + 7.1^2)^{0.5}$).

It has been shown that Reynolds number does not have considerable effects on the C_d ratio of all double-layer screens at all s/d ratios and at velocities greater than 11 m/s. This indicates the drag coefficient of double-layer screens at velocities greater than 11 m/s could be estimated by multiplying the results obtained from the computational equation presented for single-layer screens and a coefficient which depends on the s/d ratio and the porosity of the screen (and not to the Reynolds number or to the velocity).

It was observed that the Reynolds number is virtually unrelated to the ratio of the experimental C_d to the computational C_d (equation (1)) for single-layer screens. This makes it possible to define and calculate a correction coefficient for each single layer-screen. The correction ratio is 1.01, 0.92, and 0.82 for the single-layer screens at porosities of 0.34, 0.57, and 0.67 respectively. The experimental C_d of the single-layer screens without fluctuations can be calculated by multiplying the computational C_d with the correction ratio. In next step, the ratio of experimental drag coefficient of double-layer screens at different porosities and spacing ratios with respect to those of single-layer screens are investigated. To do this, all C_d ratios presented for double-layer screens are divided by relevant correction ratio at the same porosity and the results are plotted in figure 6-a.

Figure 6-a shows the mean C_d ratio at all porosities is minimum at $s/d = 0$ but it reaches to a maximum of about 2 at $s/d = 14$. The minimum C_d ratio occurs at $s/d = 0$ and is plotted versus porosity for all tested screens in figure 6-b. According to the figure 6-b, the minimum C_d ratio is 1.37, 1.66, and 1.88 for the screens with porosities of 0.34, 0.57, and 0.67 respectively. This indicates the drag force of a double-layer screen is less than twice of that of a single-layer screen with the same porosity particularly at lower porosities if s/d ratio is less than 14. The maximum reduction of

the drag coefficient occurs at the lowest porosity (0.34) and at zero spacing and is equal to 33% ($1-1.37/2$). At $s/d > 14$, the drag coefficient ratio is about 2. The figure 6-b indicates this ratio could be 11% greater than 2 (2.22) at porosity 0.67 which could be due to the experimental errors (13.8%) or underestimating the drag force acting on the frame. It should be noted that the air velocity at the centre of the wind tunnel is registered as the air velocity acting on the frame. While this assumption might be true in the case of low porosity screens, it causes error in the case of single frame. In the case of single frame, air can move around the frame and actual air velocity acting on the frame is less than the air velocity at the centre of the wind tunnel, consequently the measured drag force was registered for a wrong high velocity.

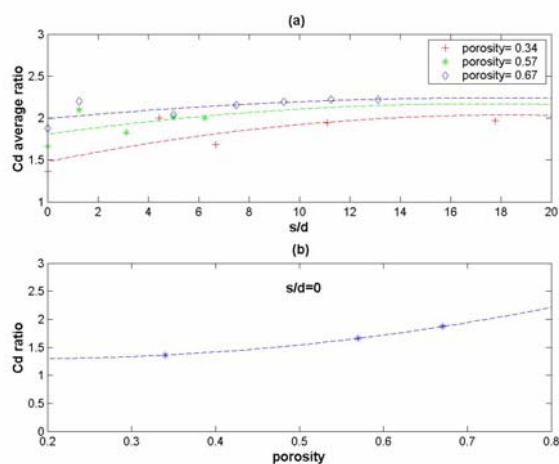


Figure 6. (a) The ratio of experimental drag coefficient of double-layer screen to adjusted experimental drag coefficient of single-layer screen versus spacing ratio (s/d) at different porosities, (b) the ratio of experimental drag coefficient of double-layer screen to adjusted experimental drag coefficient of single-layer screen at zero spacing versus porosity.

Figure 5 shows that by placing double-layer screens in the wind tunnel and increasing the s/d ratios, the wind speed and consequently the drag force decreases. In an open area application, where air can move freely around the screen, a more intense reduction of the wind speed and drag force is expected.

Conclusion

Single-layer, square cell, plain woven screens with porosities of 0.34, 0.57 and 0.67 and Reynolds number between 111 and 2890 have been tested to determine the drag coefficient and to compare the results with those obtained from the computational equation presented in [12]. According to initial inspection, commercial low-cost screens indicate inconsistency in the cell size but the experimental and computational drag coefficient show relatively good agreement with error up to 26.6%.

Two layers of the above screens with spacing ratios between zero and 17.78 have been tested to determine the drag coefficient characteristics. The Reynolds numbers have been from 111 to 2854 ($V=4.16$ m/s to $V=29.19$ m/s). The experiments for the low-cost screens which could not be properly aligned indicate that the drag coefficient of double-layer screen;

- is greater than the drag coefficient of single-layer screen at all porosities (0.34, 0.57, 0.67) and spacing ratios,
- is less than twice of the drag coefficient of single-layer screen at zero spacing. The maximum reduction of the drag coefficient between double-layer screens and twice of similar single-layer screens is moderate (33%) at porosity of 0.34 and is insignificant (6%) at porosity of 0.67,

- increases by increasing the spacing ratio and reaches to a constant value at spacing ratio of 14.

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