THERMAL LOAD AND WALL HEAT FLUX CHARACTERIZATIONS OF A PRESSURE GAIN COMBUSTOR IN LONG DURATION TESTS

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This paper focuses on experimentally investigating the thermal characterizations of a pressure gain combustor (PGC), and accordingly, a water-cooling jacket was employed to actively protect the PGC for long-duration tests. The continuous detonation was initiated via a pre-detonator and continuously fueled with the non-premixed ethylene-air mixture. During the experiments, the air mass flow rate was maintained at ~0.15 kg/s. Different equivalence ratios ranging from ~0.77 to ~1.53 have been evaluated. With the armor of the water jacket, the PGC walls were sufficiently cooled, which protected the PGC structures in the long-duration tests up to 60 seconds. The thermal loads on the PGC walls were measured through examining the water temperature rises between the inlet and outlet of the cooling jacket for the combustor inner and outer walls, respectively. Meanwhile, an E-type fast-response thermocouple was employed to probe the wall heat flux in the vicinity of the detonation front. The results show the detonation waves can propagate stably with their characteristic velocities across long-time scales. Although multiple wave modes have been observed at different equivalence ratios, no time-variation of the wave mode is found in the middle of any test when the operating conditions are precisely fixed. The bulk thermal load on the PGC inner wall is shown to be higher than the outer wall for all equivalence ratios, and the outer wall always takes a longer time to reach the thermally stable state. A significant rise of PGC thermal loads has been recorded when equivalence ratio increases from ~0.81 to ~0.99, which is found to be associated with a transition of the detonation wave mode. The thermal characterizations and the related wave mode dynamics are further discussed through the spectral analyses on the instantaneous wall heat fluxes. The experimental data of the current long-duration tests shed light on understanding the PGC thermal behaviors and provide references for estimating the required cooling capacity regarding the PGC thermal management.

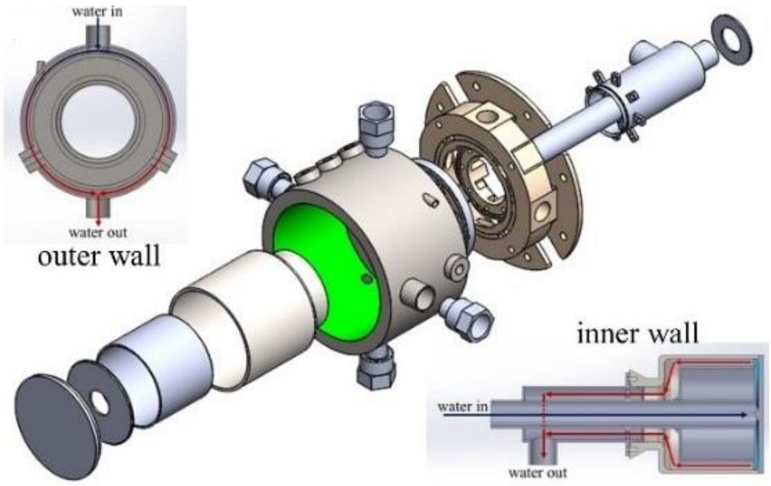

Fig 1. (a) A schematic drawing of the PGC with the water cooling jacket. (b) The experimental set-up of the water-cooled PGC.

A schematic drawing of the PGC equipped with the water cooling jacket is shown in figure 1. For the combustion region, the PGC has an outer wall diameter of 140.0 mm, an inner wall diameter of 105.5 mm, and a length of 100 mm, which keeps the same dimensions as our earlier PGC study. The fuel and oxidizer are ethylene (C_2H_4) and air, respectively. Four K-type thermocouples (Omega TJ36, Inconel) were placed at two water inlets and two water outlets, respectively, to measure the bulk thermal loads on the PGC walls. Meanwhile, one PCB 113B24 pressure sensor (sampled at 500 kHz with a high-speed NI DAQ system) and an E-type Müller instruments MCT-19 thermocouple (3 μs response time, sampled at 200 kHz with a Dewesoft SIRIUSi DAQ system) were assembled on the combustor outer wall where is 8 mm downstream of the fuel injection plane to probe the instantaneous phenomena associated with the detonation-wave-induced pressure and heat fluctuations. For the current experiments, the air mass flow rate was maintained at ~0.15 kg/s and various equivalence ratios from ~0.77 to ~1.53 were evaluated. Relying on the fast-response feature of the thermocouple, the heat flux traces can be calculated from the temperature traces by assuming the heat flux is conducted into a semi-infinite body. The equation is

$$q(t_n) = \frac{2\sqrt{\rho c k}}{\sqrt{\pi}} \sum_{i=1}^{n} \frac{T(t_i) - T(t_{i-1})}{(t_n - t_i)^{1/2} + (t_n - t_{i-1})^{1/2}} \quad (1)$$

where $\sqrt{\rho c k}$ is a known thermal property provided in the manufacturer report. With the uses of the fast-response thermocouple and the water jacket, both the instantaneous heat flux and the bulk thermal loads on the PGC walls are able to be measured simultaneously.

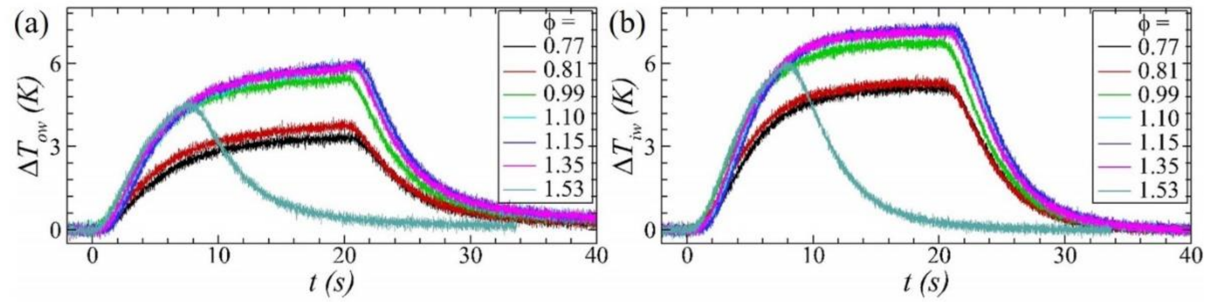

Fig 2. Cooling water temperature rises for 20-second tests with different equivalence ratios at (a) the combustor outer wall and (b) the inner wall. For all cases in this figure, both $\dot{V}_{w,iw}$ and $\dot{V}_{w,ow}$ are fixed at 45 l/min.

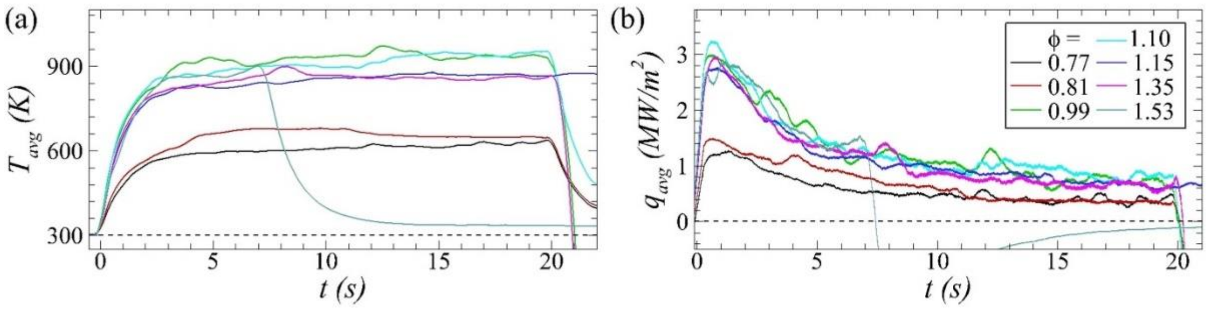

Fig 3. Moving averaged (a) temperature traces and (b) heat flux traces measure by the fast-response thermocouple for 20-second tests at different equivalence ratios. Both $\dot{V}_{w,iw}$ and $\dot{V}_{w,ow}$ are fixed at 45 l/min for all these cases.

The equivalence ratio is found to be a significant parameter that affects the detonation combustion. For the continuous detonation, the wave mode can be varied by changing the equivalence ratio. Moreover, the thermodynamics associated with the detonation wave dynamics can also be affected by the equivalence ratio, which requires to be investigated. Accordingly, a range of the equivalence ratio from ~0.77 to ~1.53 is chosen to be evaluated. The testing duration of 20 seconds is found to be acceptable to estimate the bulk thermal loads as both the outer and inner wall cooling water temperatures almost approach to their stable states at around 20 seconds, which is also a compromise due to the experimental safety considerations, especially for the fuel-rich cases. Consequently, the effects of the equivalence ratio are investigated with a testing duration of 20 seconds, as exhibited in figure 2(a) and (b). The fuel supply was terminated at around 7 seconds during the test of ϕ = ~1.53, due to the redundant fuel was sensed by a gas detector located inside the test cell and triggered the safety interlock. Apart from it, other tests all reached the targeted 20-second duration. The results show there is a significant leap of the thermal load between ϕ = ~0.81 and ~0.99, which divides the rises of the cooling water temperatures into two distinct levels. The leap is inferred to be associated with a wave mode transition, which will be discussed through the spectral analyses. Additionally, the bulk thermal load on the combustor inner wall is higher than the outer wall for all tested equivalence ratios. The leap of the thermal load regarding the wave mode change is also sensed by the fast-response thermocouple. The moving averaged outer wall temperatures and the corresponding heat flux traces are shown in figure 3(a) and (b), respectively. The local wall temperature within the detonation front increases to ~900 K for stoichiometric and fuel-rich conditions and ~600K for fuel-lean conditions. Accordingly, the moving averaged heat fluxes also fall into two magnitude levels at the ends of the tests, displaying ~0.7 MW/m^2 for stoichiometric and fuel-rich conditions and ~0.4 MW/m^2 for fuel-lean conditions. It has to be further noted that the leap of the wall heat flux is directly correlated to the wave mode transition, which is a result of the change of equivalence ratio. Consequently, a maximum of 41.2 kW cooling capacity is required for the current PGC when the single wave component is in dominance typically at fuel-rich conditions, and a minimum of 26.5 kW cooling capacity is needed when the wave pair is in dominance at fuel-lean conditions. The significant difference of the thermal behavior between the different wave modes needs to be considered in the PGC design, especially at the critical condition when the wave mode transition happens.