AIAA 2003-6486
HEAT TRANSFER AND THERMAL MANAGEMENT IN A PULSED DETONATION ENGINE

John Hoke* Royce Bradley*, and Frederick Schauer
Air Force Research Laboratory, Propulsion Directorate
Wright-Patterson AFB, OH 45433
*Innovative Scientific Solutions, Inc.
Dayton, OH 45440

41th AIAA Aerospace Sciences Meeting & Exhibit
6-9 January 2003
Reno, NV

AIAA 2003-6486

HEAT TRANSFER AND THERMAL MANAGEMENT IN A PULSED DETONATION ENGINE

John Hoke and Royce Bradley
Innovative Scientific Solutions Inc
2766 Indian Ripple Rd
Dayton, OH 45440

Frederick Schauer
Air Force Research Labs
Wright-Patterson Air Force Base
Dayton, OH 45433

Abstract

The unsteady nature of the Pulsed Detonation Engine (PDE) cycle creates a thermal environment fundamentally different from steady flow cycles. Gas velocities in a detonation tube range from O(-1) to O(1000) within a single cycle. This broad range of velocities and flow reversal make it difficult to determine analytically the contribution to the heat load from the purging, filling, detonating, and blow down portions of the cycle. In this paper, the overall heat load on a detonation tube is measured calorimetrically in an aluminum water-cooled detonation tube. The effects of operating parameters such as fill fraction, purge fraction, ignition delay, equivalence ratio, and cycle frequency are examined. Equivalence ratio and cycle frequency are found to have the largest effect on detonator tube heat load.

Introduction

Questions have arisen as to the thermal load of a pulsed detonation engine (PDE). Lower heat loads than experienced in conventional turbines are expected since the detonating portion of the cycle is relatively short; however, the temperatures and velocities of the flow during this period are higher than in conventional devices and potentially lead to higher heat loads. In this paper, heat-loads on the detonator tube of a PDE under several different operation conditions are experimentally measured and presented. Previously, Eidelman *et al*. (2001) have performed numerical simulations to determine the transient temperature profile, the rise time and steady state temperature along the detonation tube. Ajmani and Breisacher (2002) have modeled the heat flux to a detonator tube and present several measurements using heat flux gauges. Here, the overall heat load on the detonator tube is measured calorimetrically, while tube wall temperatures are measured in separate experiments using thermocouples spot-welded to the detonator tube.

Experimental Apparatus and Procedure

Experiments were performed on a 36" (0.91m) detonation tube at the Air Force Research Lab's Pulsed Detonation Research Facility. This facility was described in detail by Schauer *et al.*(2001), and only the details pertinent to this study are given here. The experiments were conducted with a spark-ignited hydrogen-air PDE. The cycle of the research Pulsed Detonation Engine (PDE) was divided into three temporally equal portions: i) detonation window, a third of the cycle is allotted for detonation initiation and blow-down. Depending on the cycle frequency, a portion of the time in this window was unused. ii) purge process, a third of the cycle was used to pump air into the detonation tube to separate the exhaust products from the pre-mixed fuel-air charge and to cool the internal geometry. iii) fill process, during the last third of the cycle, a pre-mixed charge of fuel and air was pumped into the detonation tube.

The fuel and airflow into the detonation tube were measured using a choked nozzle and choked orifices respectively. The flow rates were actively controlled by measuring the flow rate and adjusting the pressure upstream of the measuring devise to achieve the desired flow rate. The desired flow rates were calculated from the detonation tube volume, operating frequency and atmospheric pressure. With the flow control system, the equivalence ratio (ϕ), tube fill fraction (FF), and purge fraction (PF) could be adjusted with the engine running. The FF and PF are defined as the fraction of the detonation tube volume filled during the filling and purging process respectively.

A water-cooled detonation tube was constructed by inserting the 2"schedule 40 aluminum detonation tube into a 2.5" schedule 40 aluminum tube of similar length. The tubes were oriented to be concentric and the space between the tubes at either end was welded closed. Water entered the cavity between the two concentric aluminum tubes at the head end of the detonation tube and exited at the tail of the detonation tube. Type T thermocouples inserted in the water flow were used to measure the inlet and exit temperatures of the cooling water. The water flow rate was measured by a rotometer. The heat load on the detonation tube could then be calculated. The absolute error in the heat load calculated was approximately 15% due to measurement error, conduction losses and convection losses from the outer water jacket. The relative error between experiments was much less being dominated by the measurement errors and was less than 7%.

Thermocouples were also used on un-cooled detonation tubes to determine thermal rise time and equilibrium temperatures. The thermocouples were spot-welded at intervals along the detonation tube. Accuracy of the high temperature thermocouple measurements was estimated to be ± 50 °F.

Experimental Results and Analysis

The effect of frequency, fill fraction, ignition delay, equivalence ration and purge fraction on the overall heat load was investigated. The equivalence ratio was found to have the largest impact on detonator tube heat load, see Fig. 1. The heat load at 20 Hz increased almost linearly from 0 to 21.8 kW as the equivalence ratio was increased from 0 to 1. Below an equivalence ratio of 0.5 it became increasingly difficult to achieve a detonation in the 36" (.91 m) detonation tube using a deflagration to detonation transition and the heat load measured was lower than that predicted using the measurements recorded at higher equivalence ratios. Experiments were not conducted above an equivalence ratio of one.

The influence that frequency has on heat load is shown in Fig. 2. Note that unlike thrust, doubling the frequency from 20 to 40 Hz does not double the detonator tube heat load but only increased the heat load by 58%. As the frequency increases the number of detonations

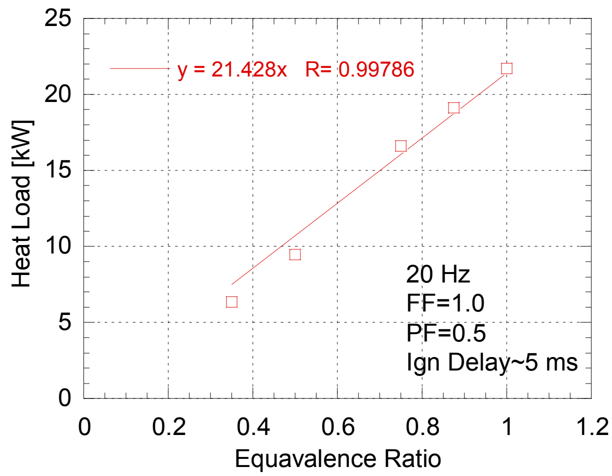

Figure 1 Heat load verses equivalence ratio, 36" (.91m) detonation tube

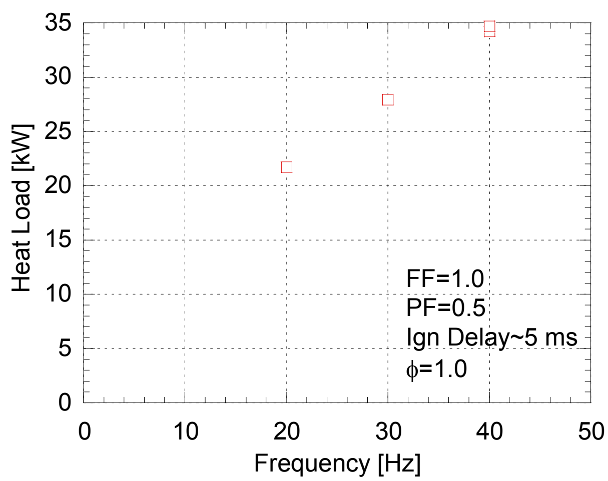

Figure 2. Heat load verses frequency, 36" (.91m) detonation tube

increased but the time for each portion of the cycle was fixed, and the time that the exhaust products (after blow-down) remained in the detonator tube decreased with increasing frequency. Additionally, the average velocity of the fill and purge increased with increasing frequency. For fully developed flow in a smooth pipe, the heat transfer coefficient increases by velocity to the 0.8 power according to the Dittus-Bolter correlation (White 1988). Therefore, at the higher frequencies, the purge and fill process would be more effective at removing heat from the detonation tube. Because of the developing boundary layer, the heat transfer coefficient was expected to be significantly higher than that predicted by Dittus-Bolter. The heat flux during the fill and purge process was not measured in these experiments.

Decreasing the fill fraction of the detonation tube decreases the heat load; however, since the exhaust products must exit through the unfilled portion of the detonation tube, the decrease in heat load was not as pronounced as that found for equivalence ratio. If Fig. 3, the heat load on the detonation tube is shown to decrease by only 19% between a fill fraction of 1 and 0.5. At a fill fraction of 0.5, the PDE was consuming half of the fuel that it would be consuming at a fill fraction of 1, and 14% less fuel than it would consume at an equivalence ratio of 0.5 and a fill faction of 1. Even though the PDE was using 14% less fuel at a fill fraction of 0.5 than it was at an equivalence ratio of 0.5 and a full fill fraction, the fuel distribution in the detonation tube created a 62% difference in heat load. The lower fuel consumption condition of FF=0.5, ϕ =1 had the higher heat load. The majority of this difference was attributed to the theoretically lower exhaust temperatures of the 0.5 equivalence ratio condition.

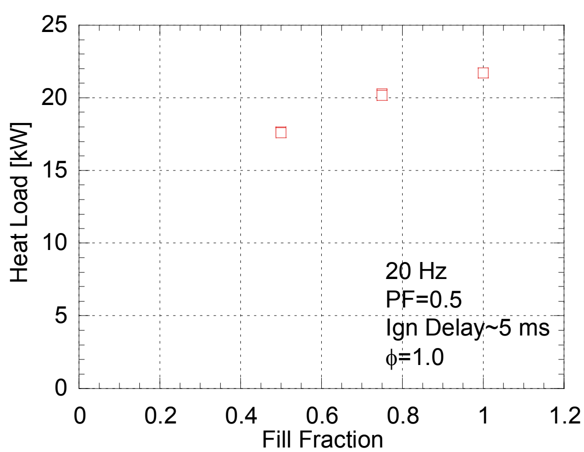

Figure 3. Heat load verses fill fraction, 36" (.91m) detonation tube

The purge fraction had a limited affect on tube heat load and in Fig. 4, the effect of purge faction on tube heat load is shown for two frequencies, 20 and 35 Hz. At 20 Hz, increasing the purge air from .25 to 1.25reduced the tube heat load by a kilo-watt. At 35 Hz, this effect was almost doubled and attributed to the higher purge velocities and greater purge mass flow required for the higher frequency.

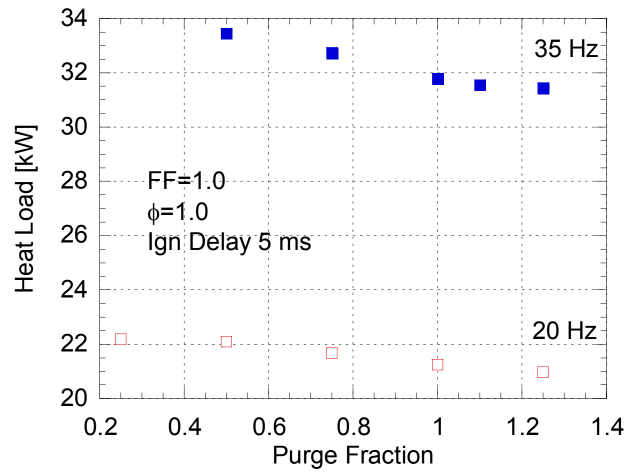

Figure 4. Heat load verses purge fraction, 36" (.91m) detonation tube

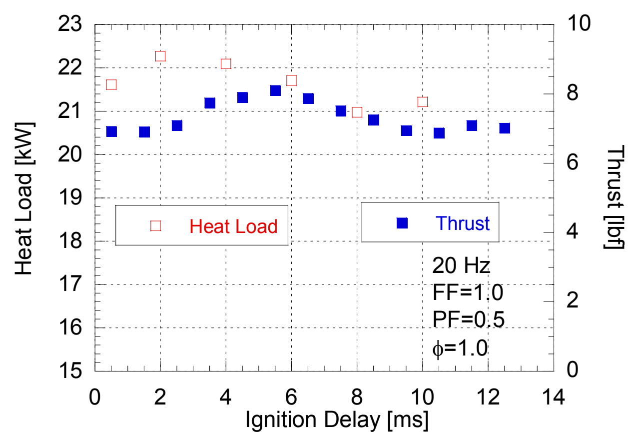

Figure 5. Heat load verses ignition delay, 36" (.91m) detonation tube

Lastly, the tube heat load was measured as a function of ignition delay. This parameter affects the time that the exhaust products remain in the detonation tube as well as the initial pressure at which the mixture was detonated, see Hoke *et al*. (2002). The heat load on the detonation tube varied approximately 1.5 kW with ignition delay, see Fig. 5. The maximum thrust occurred at an ignition delay of approximately 5 ms and the maximum heat load occurred earlier, between 2 and 4 ms. There are only small differences in the combustion temperatures with initial pressure, however, there can be a significant difference in thrust pressure. The higher thrust pressure leads to higher heat transfer however, the longer residence time of the early ignition will also contribute to higher heat loads. Therefore, the peak of heat load occurs before the peak in thrust.

The heat load on an un-cooled detonation tube should be lower than that measured for the cooled detonation tube because the temperature difference between the exhaust gases and tube walls will be smaller. Shown in Fig.6 are outside wall temperatures along the length of a 72" detonation tube that was run to thermal equilibrium. The temperature along the detonation tube varied over 300 °F and thermal equilibrium was reached in approximately 2

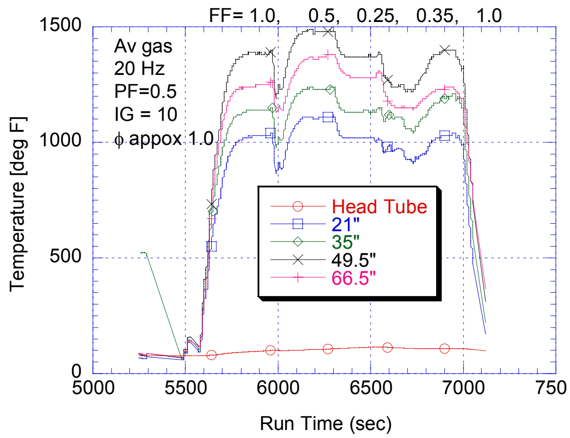

Figure 6. Detonation tube temperatures verses run time for several fill fractions, 72" (1.83m) detonation tube

minutes. The hottest region on the detonation tube occured in the region where transition from deflagration to detonation occurred. In this transition region, an overdriven detonation, with higher wave velocities, and pressures, increased the heat transfer to the tube wall. The fill fraction of the detonation was varied during this experiment and the heat load for a 72" detonation tube appeared to be higher at a fill fraction of 0.5 than at a fill fraction of 1. This was contrary to the results found for the shorter 36" detonation tube. At lower fill fractions, the peak temperatures decreased and a detonation wave was not produces since transition from deflagration to detonation occurred around 48" from the closed end of the detonation tube.

Summary and Conclusions

Although cooled-wall heat load measurements will not produce identical results to hot wall tests, the results found in this study give some indication as to the sensitivity of heat load to the significant parameters. From this study, it is evident that PDE's should be run at lower frequencies for lower heat loads; however, the heat load per unit thrust is lower at higher frequencies. Additionally, throttling of the PDE resulted in lower tube heat loads if the throttling is done by lowering the equivalence ratio rather than decreasing the fill fraction. The ignition delay or cycle of the PDE should be designed to minimize the length of time the exhaust products remain in the detonation tube after blow-down. Additionally, there are aspiration issues that encourage minimization of the time the exhaust gasses stay in the detonation tube after blow-down. Experiments with longer and larger diameter detonation tubes are planned as well as a numerical model.

Acknowledgements

Gratitude is expressed to the technicians who worked on this project: Curtis Rice, Walt Balster and Dwight Fox (ISSI). The authors would also like to thank Jeff Stutrud (AFRL/PRTS) for his computer programs used to collect and analyze the data. The technical leadership of Dr. Mel Roquemore and Dr. Robert Hancock (AFRL/PRTS) continues to be invaluable. Funding was provided by the propulsion directorate and Dr. Julian Tishkoff at AFOSR.

References

Ajmani, K. and K. J. Breisacher (2002). Qualitative Study of Cooling Methods for a Pulse-Detonation Engine. 51st JANNAF Propulsion Meeting, Lake Buena Vista, Florida, Chemical Propulsion Information Agency.

Eidelman, S., D. Sharov and D. Book (2001). The Thermal Balance of PDE. Computational Methods and Experimental Measures: 711-720.

Hoke, J. L., R. P. Bradley and F. R. Schauer (2002). The Effect of the Dynamic Filling Process on PDE Perfomance and Nozzle Selection. 51st JANNAF Propulsion Meeting, Lake Buena Vista, Florida, Chemical Propulsion Information Agency.

Schauer, F., J. Stutrud and R. Bradley (2001). Detonation Initiation Studies and Performance results for PDE Applications. 39th AIAA Aerospace Sciences Meeting and Exhibit, Reno, AIAA.

White, F. M. (1988). Heat and Mass Transfer. New York, Addison-Wesley Publishing Co.