TIME-RESOLVED HEAT TRANSFER IN ENGINE INTAKE MANIFOLD

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In this paper the authors present the development and application of transient heat transfer models to the intake manifold of a spark ignition engine. Heat transfer is an important process in the intake manifold of engines. It increases the charge temperature which reduces the volumetric efficiency and the tolerance to engine knock, and also causes higher chemical reaction rates leading to increased NOx emissions. It also affects engine performance and emissions through enhancing the fuel evaporation and charge mixing process in the engine intake ports and cylinders. For these reasons, many experimental and theoretical studies have investigated heat transfer in the intake manifold of engines.

The analytical tools widely used for estimating convective heat transfer coefficient in the intake manifolds of engines are correlations in the form of $Nu = a\,Re^b$ or $Nu = a\,Re^b\,Pr^n$ which differ only by the empirically fitted constants a, b and n [1, to 5]. These correlations provide reasonable agreement with experimental data in fully-developed steady pipe flows and acceptable agreement with time-resolved experimental data in unsteady flows with slow velocity variation, assuming they can be treated as quasi-steady. However, for highly unsteady flows with rapid velocity variations, these correlations can produce large errors in both phase and amplitude.

During one engine operating cycle, the air motion in the intake manifold encompasses approximately two phases which closely correspond to the open and closed durations of the intake valve. Phase I is an air induction phase and phase II an air oscillation-decay phase. The literature survey shows that the transient air motion in the intake manifold affects the heat transfer characteristics significantly. For instance, the study of Bauer et al. [6] has shown that measured heat transfer was 50% to 100% higher than predictions based on the Ditus-Boelter correlation and lasted longer; in terms of phasing, measured heat flux lagged behind predicted heat flux (see Figure 1). These results show that for the highly unsteady flows in the intake manifold of engines, it is inappropriate to assume quasi-steady behavior for the prediction of time-resolved heat transfer. Nevertheless, so far only few unsteady heat transfer correlations have been reported.

In our formulation, two different approaches are adopted to calculate the unsteady heat transfer rate for phase I, the air induction phase, and for phase II, the air oscillation-decay phase in the intake manifold of an engine. For phase I, assuming incompressible flow, a non-dimensional analysis of the momentum equation applied to the boundary layer yields a dimensionless variable $(D/U^2)(dU/dt)$ that represents the dynamic effect of the boundary layer. Subsequently, a dynamic variable concept is proposed to use this dimensionless variable to extend the steady correlation to a transient correlation, as follows:

$$Nu_D = C_1 \, Re_D^b \, Pr^n \left(1 + C_2 \, \frac{D}{U^2} \frac{dU}{dt} \right)^b \tag{1}$$

where b and n are equal to 0.8 and 0.4, respectively; C_1, C_2 are calibration constants, D the hydraulic diameter of the intake manifold, U the air velocity in the centerline of the intake manifold, and Re_D the Reynolds number based on D and U. Equation (1) indicates that the time-resolved heat transfer coefficient is not only a function of the Reynolds and Prandtl numbers, but also a function of the changing rates of velocity. At the limit of steady flows, the transient correlation collapses to the steady correlation.

The turbulence generated in phase I decays in phase II. The experimental data of Bauer et al [6], as well as the CFD simulation results of Manlan and Johntson [7] show that heat transfer in phase II is dominated by the turbulence decay process. Equation (2) is therefore adopted to describe the turbulence decay at Taylor's micro-scale and its associated heat transfer [7, 8].

$$Nu_\lambda = C_3 \, Re_\lambda^d \quad \text{and} \quad \frac{d(\nu / u'^2)}{dt} = \frac{10}{Re_\lambda^2} \tag{2}$$

where C_3 is a calibration constant and d is 0.75, λ is the Taylor's length scale, u' is the turbulence intensity, ν is the kinematic viscosity of air, and Re_λ is based on λ and u'.

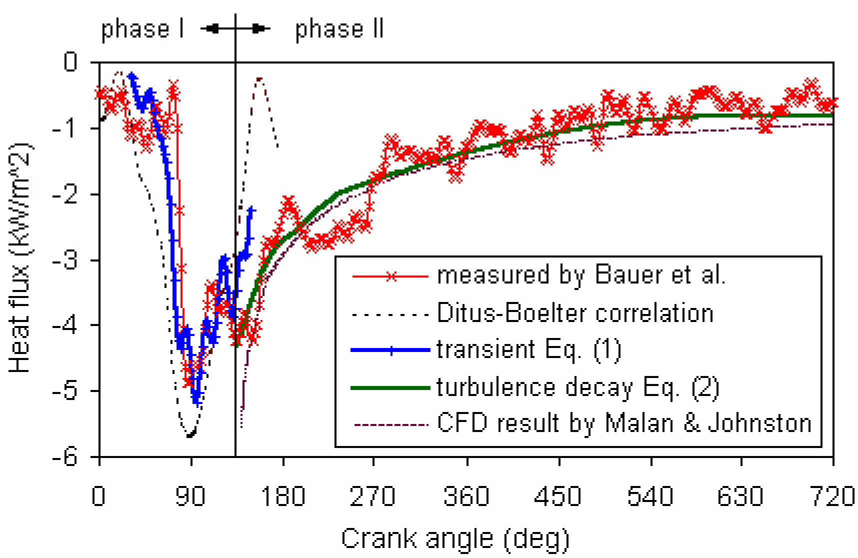

Figure 1. Comparisons between measured and predicted heat flux

As shown in Figure 1, the calibration constants $C_1 = 0.018$, $C_2 = -0.75$ and $C_3 = 14.80$ are found to match the measured heat flux data during phase I and phase II.

CONCLUSIONS

In this paper, the authors developed and applied an unsteady model for the prediction of the time-resolved heat transfer in the intake manifold of an engine. Based on experimental and theoretical analyses, the authors showed that heat transfer in the intake manifold of an engine should be divided into two phases according to their distinct heat transfer mechanisms, one describing the air induction phase I, and the second describing the air oscillation-decay phase II. Accordingly, the authors have proposed the unsteady heat transfer model described by Equations (1) and (2). These equations indicate that the heat transfer coefficient is not only a function of the Reynolds and Prandtl numbers, but also a function of the changing rates of the velocity and turbulence intensity. The dimensionless variable $(D/U^2)(dU/dt)$ and the turbulence decay equation can further be used to investigate the transient criteria of the unsteady flows. Comparisons between the measured and predicted heat flux (figure 1) show that the transient model equation (1) corrects the phase error generated by using the steady-state Ditus-Boelter correlation and equation (2) captures heat transfer during the turbulent decay process. Since the model equations have been developed based on general mechanisms of unsteady turbulent flows, they should be applicable to estimating other engineering heat transfer processes in similar situations.

REFERENCES

1. Dittus, F. W. and Boelter, L. M. K., Heat Transfer in Automobile Radiators of the Tubular Type, Univ. of California Pub. Eng., Vol. 2, No. 13, pp. 443-461, Oct. 17, 1930; reprinted in *Int. Comm., Heat Mass Transfer*, Vol. 12, 1985, pp. 3-22.
2. Colburn, A. P., A Method of Correlating Forced Convection Heat Transfer Data and Comparison with Fluid Friction, Trans. Am. Inst. Chem. Eng., Vol. 29 1933, pp. 174 -210; reprinted in *Int. J. Heat Mass Transfer*, Vol. 7, 1964, pp. 1359-1384.
3. Shayler, P. J., Colechin M. J. F. and Scarisbrick, A., Heat Transfer Measurements in the Intake Port of a Spark Ignition Engine, SAE paper 960273.
4. Martins, J. J. G. and Finlay, I. C., Heat Transfer to Air-Ethanol and Air-Methanol Sprays Flowing in Heated Ducts and Across Heated Intake Valves, SAE Paper 900583
5. C. Depcik and D. N. Assanis, “A Universal Heat Transfer Correlation for Intake and Exhaust Flows in an Spark Ignition Internal Combustion Engine,” SAE Paper 2002-01-0372
6. W. D. Bauer, J. Wenisch and J. B. Heywood, “Averaged and Time-Resolved Heat Transfer of Steady and Pulsating Entry Flow in Intake Manifold of a Spark-Ignition Engine,” *Int. J. Heat and Fluid Flow*, 19 (1998), pp. 1-9.
7. P. Malan, J. P. Johnston, “Heat Transfer in Shear Free Turbulent Boundary Layers.” Thermo-sciences Division, Department of Mechanical Engineering, Stanford University, Stanford, CA, Report MD-64. 1993
8. A. J. Reynolds, “ Turbulent Flows in Engineering.” John Wiley & Sons, Ltd., 1974