

Determination of the Cylinder Head Valve Bridge Temperatures in the Concept Phase Using a Novel 1D Calculation Approach

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ABSTRACT

The steady increase of engine power and the demand of lightweight design along with enhanced reliability require an optimized dimensioning process, especially in cylinder head valve bridge, which is progressively prone to cracking. The problems leading to valve bridge cracking are high temperatures and temperature gradients on one hand and high mechanical restraining on the other hand. The accurate temperature estimation at the valve bridge center has significant outcomes for valve bridge thickness and width optimization.

This paper presents a 1D heat transfer model, which is constructed through the cross section of the valve bridge center by the use of well known quasi-stationary heat convection and conduction equations and reduced from 3D to 1D via regression and empirical weighting coefficients. Several diesel engine cylinder heads with different application types and materials are used for model setup and verification. Calculated values with the 1D model are compared with the 3D finite element analysis results for exhaust-exhaust and exhaust-intake valve bridges, where estimated results lie in a ± 6 °C error interval showing a reasonable approximation. The proposed calculation method is further used to derive the sensitivity of the valve bridge temperatures on the valve bridge thickness and width, which serves as a basis for dimensional optimization under predefined temperature limits of the cylinder head material, even in the concept phase.

INTRODUCTION

The cylinder head with its asymmetrical interior shape is one of the most complicated parts of an internal combustion engine and is exposed to high combustion pressures and temperatures. The highest temperatures occur in the area of the valve bridge, where cooler peripheral zones cause thermal compression stress which is superposed by the stress due to the temperature difference between the interior and the exterior wall of the flame deck. As a result of this superposition, the compressive yield stress may be exceeded in the valve bridge area. When the flame deck cools down during part load or idling or after the engine is turned off, the compressive yield stress turns to tensile and may result in tensile yielding. If this heating and cooling process is repeated often, the dynamic strength of the material can be exceeded, which results in cracking. These cracks can lead to water penetration [1].

Valve bridges experience severe thermal loading as they receive heat not only from in-cylinder burning gases during the combustion period but also from burned gases flowing through the exhaust valve and along the exhaust port walls during the exhaust [2]. Moreover, valve bridge is the most sensitive area in terms of thermal stresses due to its smaller cross section in comparison to other locations in the cylinder head [3].

In order to minimize the thermal stress, an even temperature distribution is required, which can solve the thermomechanical fatigue (TMF) cracking. However, due to the complex shape and asymmetrical thermal loads, an even temperature distribution is not attainable. From the designer's

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viewpoint, the aim is to avoid the TMF problem at an early stage such that global design changes will not be necessary after the base design analysis. The reasons are twofold. First, the design changes to improve the TMF behavior do not necessarily prove the design. Second, the calculation loop depth due to the sensitivity of TMF to the temperature field increases the cost/time of a design iteration. Different alternatives are possible to solve TMF problems in valve bridge area. A few design alternatives are given below:

Reducing the operating temperature [4]:

- directed coolant flow over the valve bridges
- drillings close to the flame deck passing thru valve bridges
- reducing the flamedeck thickness: to improve the conductive heat transfer

Reducing mechanical restraining [5]:

- Decreasing the surrounding material stiffness relative to flame deck
- Allow for the expansion of flame deck surface by introducing grooves or slots

Reducing both the operating temperature and mechanical restraining:

- Increasing valve bridge width

Since the temperature is the dominant load, reducing the operating temperature is a proven method for improving TMF behavior of cylinder heads. Therefore, temperature estimation in an early phase of development is of utmost importance especially for today's high performance new engine designs. As the boundary conditions of modern high specific power engines are extrapolated, it is not possible to interpolate the geometric dimensions from existing designs. Under these circumstances, model-based analyses become more important to reduce prototype testing. Rather than using experimental and/or finite element analysis (FEA) techniques, usage of an analytical/empirical approach is the most cost effective and fastest way for cylinder head design once its applicability is verified.

QUASI-STATIONARY HEAT TRANSFER AT COMBUSTION CHAMBER WALL

The quasi-stationary heat flux density from the combustion gas to the coolant as well as the average gas and coolant side wall temperatures (T_{wg} , T_{wc} , respectively) can be calculated with the use of the average process variables T_g , and h_g , given design parameters t and λ , as well as cooling parameters T_c , and h_c [1], by considering the heat transfer at the combustion chamber wall as depicted in [Figure 1](#), where,

T_g : average gas temperature

h_g : average heat transfer coefficient for gas side

T_c : coolant temperature

h_c : heat transfer coefficient for coolant side

t : wall thickness

λ : thermal conductivity of wall material

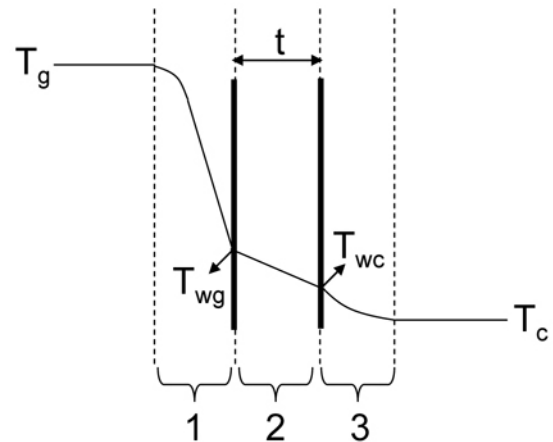


Figure 1. Heat transfer at the combustion chamber wall (flat wall)

Corresponding heat transfer equations, neglecting the radiation term for gas side, are as follows:

1. Gas side: $\phi_{\text{conv},g} = h_g \cdot (T_g - T_{wg})$ Heat convection from combustion gases to the combustion chamber wall
2. Wall: $\phi_{\text{cond}} = \lambda \cdot (T_g - T_{wg}) / t$ Heat conduction through the thickness of the combustion chamber wall
3. Coolant side: $\phi_{\text{conv},c} = h_c \cdot (T_{wc} - T_c)$ Heat convection from the combustion chamber wall to the coolant

As the valve bridge section deviates strongly from a flat wall, the above mentioned equations can not be used directly to model the heat transfer across the valve bridge. This geometric complexity generates an obstacle for analytical studies and promotes the application of 3D FEA for the estimation of temperatures.

Among the cylinder head, cylinder wall and piston surrounding the combustion chamber, most of the studies about heat transfer in combustion engines concentrated on the heat transfer between the combustion gases and cylinder wall. The most well-known approaches regarding the heat transfer in combustion engines are found by Annand, Woschni, Taylor and Toong as explained in [6], [7] and [8]. All of

them proposed a relationship between Nusselt number (Nu) and Reynolds number (Re), in order to find an expression for convective heat transfer coefficient to calculate the heat flux from combustion gases to the engine component. The correlations developed by Annand, Woschni, Taylor and Toong do not consider the local change of the temperature values, as they use spatially averaged parameters during calculation.

Sargenti [9] used a thermal network to numerically model the heat transfer in combustion engines, where calculation blocks were created for cylinder skirt, head, piston, inlet and outlet valves as well as the inlet and outlet ports. He divided the cylinder head into four regions and calculated the temporally and spatially averaged temperatures of these regions focusing on heat balance calculations and average wall temperatures but not on peak valve bridge temperatures.

As reported by Finol and Robinson [6], for thermal analysis and appropriate modeling of engine components, local heat fluxes are required with an accurate prediction. In this study, a local temperature prediction model at the valve bridge center is presented, which differs from the spatially averaged approaches of Sargenti, Annand, Woschni, Taylor and Toong. However, due to the small temperature fluctuations ($\sim 8\text{--}10^\circ\text{C}$ for aluminum and $\sim 15\text{--}20^\circ\text{C}$ for cast irons) on combustion chamber surface within an engine operating cycle, time variation of the gas side boundary conditions are of little interest and therefore cycle averaged values are used for thermal analysis of the valve bridge section.

MODEL DEVELOPMENT

One of the primary goals of cylinder head development is to reduce T_{wg} value in order to prevent low cycle thermal fatigue failure due to high temperatures [10]. For this purpose, λ and h_c values must be maximized, whereas t and h_g values should be kept as low as possible. However, these parameters may be given/fixed as boundary conditions. For example, there is not a high flexibility in the choice of material, so the thermal conductivity λ can only be increased up to a limitation [11]. In addition to that, determination of the flame deck thickness is another issue of compromise. In order to increase the heat conduction across the flame deck of the cylinder head, thickness should be decreased. Nevertheless, small flame deck thickness may not be a good design choice, since the cylinder head experiences high mechanical loads due to the high combustion pressures and its stiffness is proportional to the thickness of the flame deck [12], [13].

It is clear from the above mentioned issues that the calculation of the critical temperatures of the cylinder head plays an important role during the design stages in terms of determining the optimal geometric parameters. To contribute to the design process, a 1D heat transfer model is constructed

through the cross section of the valve bridge center by the use of well known quasi-stationary heat convection and conduction equations.

As shown in Figure 2, in the vicinity of the valve bridge center, isotherms are parallel to each other. Hence, heat transfer in z-direction can be neglected, which justifies the model reduction from 3D to 2D. A 2D representation of the valve bridge cross section with the actual and modeled views is shown in Figure 3.

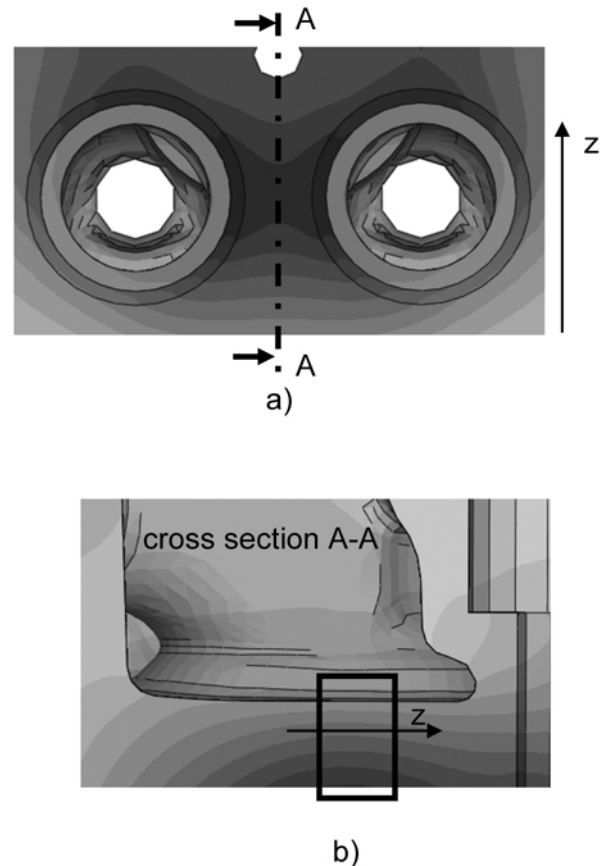


Figure 2. a) flame deck surface of a cylinder head, b) cross section A-A

In order to reduce the heat transfer model to 1D, the equations of heat convection on coolant and gas side as well as heat conduction across the valve bridge thickness are modified by multiplication with the weighting coefficients A_c , A_g , and A_{int} , which are proportional to the arc length s , reduced valve bridge width w_r (at flame face), and $(s+w_r)/2$, respectively. By trial calculations with the reduced 1D model, it is proven that the calculated valve bridge temperature values are almost same as the FEA results, if we consider w_r and s^* , which is determined by angle α^* perpendicular to the isotherms. As depicted in Figure 3, α^* gives the average perpendicularity line to the isotherms, where this line