

Real Gas Effects in High-Pressure Engine Environment

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ABSTRACT

Real gas effects are studied during the compression stroke of a diesel engine. Several different real gas models are compared to the ideal gas law and to the experimental pressure history. Comparisons are done with both 1-D and CFD simulations, and reasons and answers are found out for the observed differences between simulations and experimental data. The engine compression ratio was measured for accurate model predictions. In addition, a 300bar extreme pressure case is also analyzed with the real gas model since an engine capable for this performance level is currently being built at the Aalto University School of Science and Technology. Real gas effects are even more important in these extreme conditions than in normal operating pressures. Finally, it is shown that the predicted pressure history during an engine compression stroke by a real gas model is more accurately predicted than by the ideal gas law.

INTRODUCTION

Generally it may be said that in high pressure but low temperature conditions the deviation from the ideal gas behavior starts to be significant. Ideal gas is assumed to consist of molecules that interact with each other rarely and the collisions are elastic. In addition, the volume occupied by the gas molecules is assumed to be negligible. Real gas models typically take into account the volume of the molecules which is not insignificant in high pressure environments. In addition, the inter-molecular forces are evenly distributed within the gas but close to a wall the molecules have higher attractive force on the gas side than on the wall side (less molecules on the wall side). As gas pressure is caused by the molecules colliding with its surrounding walls, this leads to a decrease in the pressure compared to the ideal gas law.

In marine engines, the maximum cylinder pressures before combustion at full load are typically between 140 - 180bar. By applying the ideal gas law into this situation, roughly a 5% error is made in the pressure. Much higher pressures are soon going to be reached; at the Aalto University School of Science and Technology a 300bar maximum cylinder pressure engine is currently being built. In this case, the relative error in the pressure is already close to 10% if ideal gas law is used.

The main idea in increasing engine cylinder pressure is to obtain higher power density. If the increased cylinder pressure is achieved by using high compression ratio together with short combustion duration, good indicated efficiency can also be expected. The drawback is that the engine component design becomes more demanding. Extreme cylinder pressures may also necessitate redesign of the combustion process as the gas density is much higher. The fuel sprays might be influenced by the higher gas density. However, this paper concentrates to the compression stroke pressure prior to combustion.

The real gas behavior during the engine compression stroke has not been very popular topic if the amount of publications is considered. Renz et al. [1] and Taskinen [2] used several different real gas equations for the modeling of a marine engine but did not focus on the compression stroke nor to the specific real gas effects. The main idea in their work was to use more advanced evaporation models for which real gas modeling was needed.

In this paper, experimental engine pressure data is compared to computational ones during the compression stroke in a high load case. 1-D and CFD results are compared with both ideal and real gas models. Reasons and explanations are also found out for the differences observed in the results compared to experiments.

It was found out that typically the ideal gas law underestimates the compression stroke pressure at top dead centre (tdc) position compared to measurements. Real gas models give higher pressure at tdc position than the ideal gas law. The real gas models implemented into the CFD code seem to overestimate the pressure at tdc. However, with detailed analysis it was found out that the overprediction in the pressure produced by the real gas model is the correct result in terms of other relevant phenomena that are observed in engines but which are not taken into account in these simulations. These phenomena include effects from cylinder air blowby, deformation of combustion chamber components due to high pressure, valve timing, and heat transfer.

IDEAL AND REAL GASES

Ideal gas is assumed to consist of molecules which have negligible volume, and that the collisions between the molecules are rare and elastic. In many cases the ideal gas law which is based on these approximations gives very accurate predictions. However, in high-pressure environment and, as we will see later, especially if temperature is low at the same time, the deviation from the ideal gas behaviour is big. This is because in high-pressure environment the volume occupied by the gas molecules is increasingly important (higher density). On the other hand, in low-temperature environment the relative portion of the molecule's kinetic energy (which is largely due to temperature) is lower compared to the inter-molecule forces acting between real molecules. [3]

The non-ideality of a gas is conveniently expressed by the compressibility factor Z

$$Z = \frac{PV}{RT} \quad (1)$$

The compressibility factor Z is often correlated with the reduced pressure $P_r = P/P_c$ and reduced temperature $T_r = T/T_c$, where P_c and T_c are the critical pressure and temperature, respectively. In the Figs. 1 and 2 is shown a generalized compressibility chart for gases [4]. It is based on measurements and it should lead to errors of less than 4 to 6 percent except near the saturation curve or near the critical point, where Z is very sensitive to both T_r and P_c . The Figs. 1 and 2 should not be used for strongly polar fluids. [3]

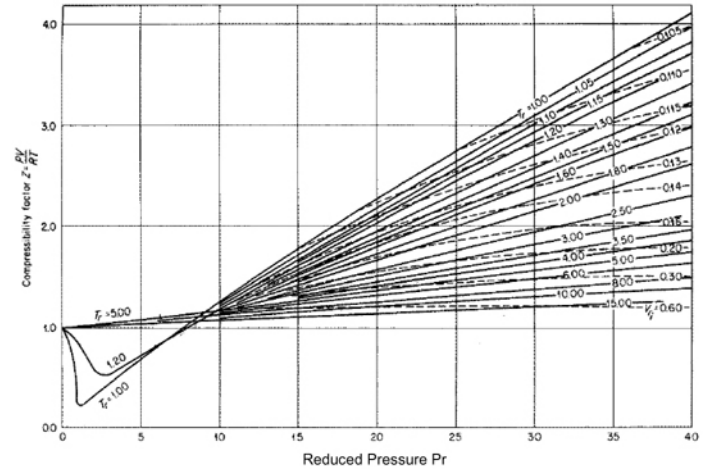


Figure 1. Generalized compressibility chart [4].

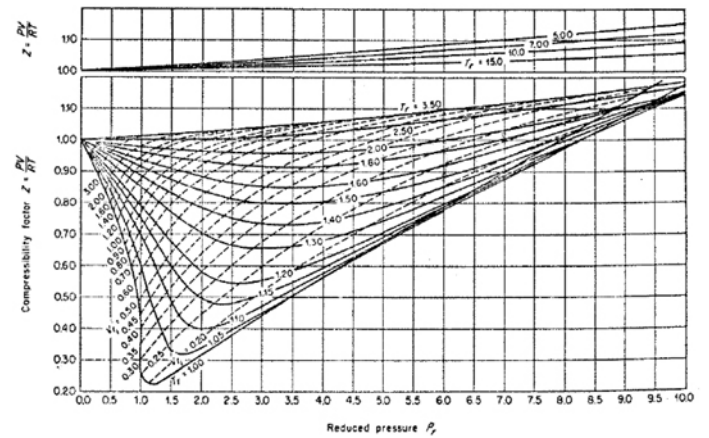


Figure 2. Generalized compressibility chart [4].

REAL GAS EQUATION

Many of the common two-parameter cubic equations can be expressed by the equation

$$P = \frac{RT}{V-b} - \frac{a}{V^2 + uV + wb^2} \quad (2)$$

Using Eq. (1) yields

$$Z^3 - (1 + B^* - uB^*)Z^2 + (A^* + wB^{*2} - uB^* - uB^{*2})Z - A^*B^* - wB^{*2} - wB^{*3} = 0 \quad (3)$$

where $A^* = aP/R^2T^2$, $B^* = bP/RT$, $a = c_a F \frac{R^2 T_c^2}{P_c}$, and $b = c_b \frac{RT_c}{P_c}$. This can be solved by Cardano's formula [5].

In this work, the Peng-Robinson [6] and the Redlich-Kwong [7] cubic equations of state are used. For them, the model parameters are listed in the Table 1. The critical properties used in this work are for oxygen $T_{c,O_2} = 154.6\text{K}$ and $P_{c,O_2} = 50.4598\text{bar}$, and for nitrogen $T_{c,N_2} = 126.2\text{K}$ and $P_{c,N_2} = 33.9439\text{bar}$. The accentric factors [3] used in the Peng-Robinson model (not needed in the Redlich-Kwong model) are $w_{O_2} = 0.025$ and $w_{N_2} = 0.039$.

It should also be noted that the above models are “user”-coded in Star-CD which means that they can be altered as wished but the Redlich-Kwong model in the 1-D code (GT-Power) can not be accessed by the user and hence the exact details of the model cannot be estimated apart from what is said in the code manual.

Table 1. Model parameters for the Peng-Robinson and Redlich-Kwong equations of state.

Eqn.	u	w	c_b	$c_a F$
Peng-Robinson	2	-1	0.07780	$0.45724F$
Redlich-Kwong	1	0	0.08664	$\frac{0.42748}{T_r^{0.5}}$
$F = \left[1 + f(w)(1 - T_r^{0.5})\right]^2$				
$f(w) = 0.37464 + 1.54226w - 0.26992w^2$				

In the Figs. 3 and 4 are shown the real gas deviation from the ideal gas law calculated by the Peng-Robinson model used in this study. As an example, in case pressure is 300bar ($P_r = 8.2$) and temperature is 1000K ($T_r = 7.7$), we obtain by the Peng-Robinson model $Z \sim 1.08$. Comparing this to the Figs. 1 and 2 shows us that the implemented real gas model performs very well.

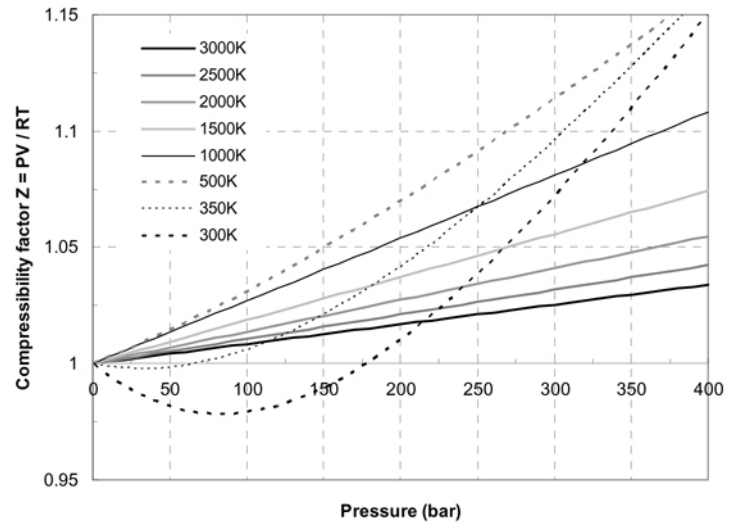


Figure 3. Conditions in diesel engine and the deviation from the ideal gas behavior. Calculated with the Peng-Robinson real gas equation.

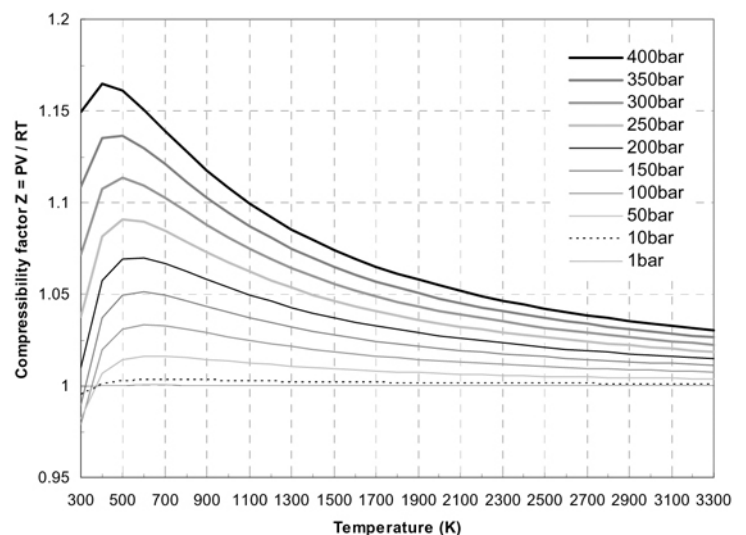


Figure 4. Conditions in diesel engine and the deviation from the ideal gas behavior. Calculated with the Peng-Robinson real gas equation.

EXPERIMENTAL ENGINE

EVE is a single-cylinder medium-speed 4-stroke diesel engine with a 200 mm bore and stroke of 280mm. The current maximum allowed cylinder pressure of EVE is about 200 bars, common rail pressure is 1400 bars and engine speed is 900 rpm. EVE has no turbo charger but a separate charge air compressor (1-8 bars). Special characteristics include electro-hydraulic control of gas exchange valves, electro-hydraulically (solenoid) controlled injection valve, operation in motored mode, easy access for measurements and possibility for optical access. [8]

