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To: **Faculty of Mechanical Engineering – Brno University of Technology**

Subject: **Review Report for a PhD Dissertation by Peter Raffai**

Dear Faculty of Mechanical Engineering,

I am happy to write this review report of the PhD Dissertation titled, "MODELING THE IMPACT OF PISTON RINGS ON OIL CONSUMPTION OF INTERNAL COMBUSTION ENGINES" by Peter Raffai. I have worked in this area since I was a PhD student studying at the University of Wisconsin-Madison (graduated 1990) and while working at Cummins Inc. (1990 to present date).

Brief Summary of the Purpose
The purpose of this thesis centered on two main goals:

1. Development of a complex simulation tool suitable for the determination of friction, lubricating oil consumption, and blow-by from various sources in an internal combustion engine.
2. Validation of the simulation tool through suitable experiments.

The algorithms developed in this thesis are intended to support the research and development of modern internal combustion engines. This is done to achieve higher effectiveness, lower losses, better fuel economy and a more sustainable exhaust gas emission in order to help make the Earth a better place to live.

This topic has been the subject of many technical papers and much research. The unique characteristic of this work is the combination of so many different elements and mechanisms to help the engine developer and researcher optimize the engine.

Review of the Analytics
The dissertation was very comprehensive in its scope and covers a wide variety of considerations that are important for modeling the engine. The dissertation starts out with a description of the model and the science behind the calculations. The thesis describes and the analytics predict the flow of the gases through the piston ring pack. The physical principals that form the basis for this model are acceptable. However the PhD candidate states that ring flutter "is not usual" and therefore simplifies the model by not considering it. Unfortunately ring flutter is very common and the effect on how gases flow around the ring when it moves is very significant. For a tool to be a successful predictor of oil consumption and blow-by axial and radial ring motion (including radial ring collapse) need to be considered in the model. Another area of improvement would be the calculation of piston ring twisting under the dynamic loading conditions on the ring.

The lubrication of the face of the piston rings are accurately considered in the thesis. The models that have been proposed represent the most current and advanced treatment of this topic. The use of lubrication "flow factors" and the treatment of different surface finish types is important. However the PhD candidate should realize that the surface finish parameters that are used in the model, are not the parameters that are used in industry to control the surface finish of the cylinder.

The mechanisms of oil consumption represent the current best understanding and appear to include the proper analytics for predictions. The model could be improved if there was some consideration of the effects of bore distortion. While the thesis describes a 2-D model of the ring pack, the three dimensional effects of bore distortion can be accommodated to some extent (reference models by Ricardo and AVL).

In summary the analytical methodologies presented are very comprehensive in scope. They include most of the important factors that are needed to predict ring pack performance. A few areas of improvement have been noted.

Review of the Experimental Studies

The engine used as a vehicle for validation of the model seems to be a good choice. The work done to prepare the input data seems appropriate. Significant work was done to characterize the surface finish to be utilized in the model. It was good to evaluate worn and unworn conditions and various materials.

The prediction of blow-by seems to correlate very well with the experimental measurements. This is as good a correlation between the prediction and measurement as I have seen. However the predicted pressure between the top and second ring does not correlate with experience. There is no variation in the pressure between the piston rings, which seems unusual.

The prediction of the oil film thickness seems to be correct and the characteristics are in the proper magnitude based on experience. Also it is good to see that the model can predict radial ring collapse. When this occurs, especially on the top compression ring, there can be a significant impact on blow-by and inter-ring gas pressure. This was not seen in the inter-ring gas pressure plots. The mechanism of how the ring can collapse when pressure and ring tension both oppose the collapse of the ring may be investigated more.

Analysis of the friction results seem very plausible and follow expected characteristics. This treatment of friction is enhanced by the ability of the code to predict the wetted surface of the ring. Some codes assume fully flooded lubrication and as a result over predict the oil film thickness. This model seems to predict well the friction characteristics of the ring. While the graphs show friction force, friction power losses are most important when developing an engine.

The prediction of oil consumption also seems reasonable. The magnitude of the predicted oil consumption seems to be in approximately the correct magnitude.

Review of the Parametric Studies

The studies of the effect of lubricant viscosity showed the expected trends suggesting the model is predicting accurately. The friction trends for different surfaces do not always follow expected trends. This is probably because the Coefficient of Friction is considered the same in the model. In reality, the Coefficient of Friction would be lower for DLC coated rings and nitrided rings. This was acknowledged in the thesis.

The conclusion in the thesis says the surface topography has very little influence on LOC. In actual engines, worn rings will have higher oil consumption. But this is most likely due to other parameter such as opening of the end gaps with wear.

Overall Summary and Recommendation

The PhD candidate has developed a comprehensive and state of the art model comprised of many factors that affect the performance of the engine. He has compiled some of the most advanced concepts and ideas into one all-encompassing model. The various sub-models contain key physical aspects representing many different areas of engineering and science that are important to obtain the goal. This produces a tool that not only helps the doctoral candidate understand and comprehend the engine better, but by documenting this collection of knowledge it significantly helps others in the industry and provides good long term reference.

While this work is very comprehensive, not everything can be accomplished at once. I agree with the PhD candidate that the next important improvement to this work is the development of relative ring motion in the ring groove including ring twist. In the more distant future, upgrading the work to three dimensional analysis (bore distortion, etc.) would be beneficial.

The PhD candidate has organized the work in a very clear and logical manner that was easy to follow. The text of the thesis was clear to read and written well. The graphs and tables were well crafted and accurately conveyed the information contained in them. Overall the PhD candidate has met the stated objectives of the thesis.

Because of the extent of this work, the quality of the material contained in this thesis, and the significant potential of this work, I recommend that the Faculty accept this thesis and the candidacy of Peter Raffai as worthy to receive his PhD.

Sincerely,

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