THE TEMPERATURE AND STRESS FIELD OF THE CERAMIC-CAPPED CYLINDER HEAD OF THE HYPOTHETICAL ADIABATIC DIESEL ENGINE

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Abstract

Four of five models of the ceramic-slab-capped cast-iron cylinder head for a prospective adiabatic engine were numerically investigated. The models were designed using several crystallochemical-mineralogical considerations. The outcome of some short radiation and convection Fortran95 programmes became the input data for the FEM programme of temperatures and stresses. It turns out, that in general the material that cannot withstand will hardly be ceramics, but the cast iron. Thence, the latter should be replaced, plated or the ceramics should cover it at the injection jet. The temperatures and stresses were analysed with and without an interlayer. Two models, with feldspars and Ti6Al4V or Pt30Au70, were quite promising, the first one being surely at once applicable even without interlayer i.e. according to FEM. The stresses in the models with YSZ, cerium disilicide and/or pyroxene, in spite of the crystallochemical hattrics deemed successful, betoken spallation of the YSZ. The problems of emissivity were addressed as well. There exists a blank range of temperature where neither radiation-related algorithm nor the common conductivity one can perform well. The surface of the head under hood appears 'quite cold', except the exhaust pipe, the TBC solution of which is left in abeyance in this paper. Adiabatic engines using ceramic as the material for the combustion camber walls were developed for the reduction of cooling loss and the in crease of exhaust energies.

Keywords: *cylinder head, PtAu alloy, thermal conductivity, thermal stress*

1. Introduction

In course of modelling elements of the prospective adiabatic engine at the occasion of the earlier author's work, 4 (5) ceramic- or composite-capped models of the head, basing on the cast iron, were launched. The hypothetical models are based on using of the anionic potential [1], i.e. diverse of diverse materials, non-classical epitaxy rules (though we are dealing with polycrystals), atomic sharpness of the phases, and several other crystallochemical or mineralogical hattrics – explanation of which is beyond the scope and purpose of this paper, but see below and the conclusion. Albeit in general case, the coefficient of thermal expansion of a material needs not to be in harmony with the other, the tendency here is that it diminishes from metal to ceramics. The used cast iron is a common one; E, 103-118 GPa, CTE, 10-13 ppm/K, and conductivity λ, 48.5-44.5 W/mK, and low hardness. The processes of joining would be pouring the metal onto ceramics and heating, sintering, but spraying is also conceivable. While joining $CeSi_2$ to pyroxene, one can imagine itself a silicidpyribol'(joining on motif, Si atoms in $CeSi_2$ are in the same place as in Si), whereas while joining YSZ and pyroxene – cuspidine (a group of silicates) might come into being, especially when the pyroxene were derived from amphiboles. The authors have to refrain from the discussion on the causes of deterioration of YSZ in engines (recrystallisation, chemical corrosion), but emissivity will be addressed, either. We are dealing with the head of an engine with cylinder of 140 mm, while assuming some loadings from the engine of 107 mm. The cerium disilicide is far from the others materials and very odd for its high-E material (269.28 GPa) to be – 539.96 VHN (re-casted from Samsonov et al. [4]). The following types were set forth:

1. YSZ –4mm/$CeSi_2$-1mm/the cast iron (TCI),
2. YSZ-4mm/clinoenstatite (pyroxene)-1mm/$CeSi_2$ - 1mm/ TCI,
3. The composite plagioclase-Ti6Al4V (74.05% vol. plagioclase)– 4mm/TCI – can be sprayed,
4. Plagioclase-3mm/Pt30Au70-1mm/TCI – the alloy can be replaced by Cr_3Si or V_3Si,
5. Scandia-4mm/Cr_3Si + V_3Si – 1mm/$TiSi_2$ + Cr-Ni – 1mm/ TCI – it can be a good ensemble, but not to adiabatic engine since the temperatures drops on scandia are too low, 275.65-193.74^o C.

To compute temperature at interfaces (also whenever possible on the cast iron/air boundary), the short junior author's programmes (radiation and convection) in FORTRAN 95 were used. The convection loadings are presented in Tab.1. Four points at every interface were computed; the input temperature partly taken from Woods et al. [5]. The modelling is of exploration character, thence, e.g. a part of the join-surface is intentionally without interlayer to explore the response of TCI on the TBC-slab (b in the tables). To depict the temperature and the stress field, ANSYS12 (13) was fed up with all the data. In the programme, there the unique convection elements of the 152-type were used as well, blocking and coupling. Replacing of a few cylindrical surfaces by the flat ones gave a bias of 0.1-0.14 mm. The analyses are nonlinear (the programme automatically switched into, surely due to temperature-dependent parameters of possibly all the materials). The pipes of similar diameter were interchanged and are any bearing on this work.

Tab. 1. The cylinder head – convection BC input data; film coeff. α [W/(m^{2}K)], temperature – ^{o} C

Environment	α	Temperature of work medium
Ambient/air	20	21.85
Air in the head*	80	75
Air in the head (engine block)	75	75
Air above head (under hood) **	75	75
Fuel (inject.)	70	20
Exhaust pipe	400$^{\#}$	800
From exhaust-valve-pin liner	200	154$^{\&}$
Intake pipe	200$^{\#}$	21.85$^{\#}$
From intake-valve-pin liner	200	69$^{\&}$
From the combustion chamber$^{\$}$	671.46	1200

*- instead of cooling agent, ** -under hood, $^{\#}$ - after Kwaśniowski et al [2], $^{\&}$ - a practical average from considerations on the pin of the valve, $^{\$}$ - the authors are aware that the to-ceramic film coefficient can be higher, but no estimation free path etc were made.

2. Modelling and results

Temperatures in the definite points of the model types are presented in the Tab. 2-5. The 1-2-3 points define section of the head through valves, the 4-point is aside, the2-one being common to the sections 1-2-3 and 2-4.

Tab. 2. The interface temperatures, the 1-type; ^{o} C

Interface	Pt.1	Pt.2	Pt.3	Pt.4
Air/TCI	91.77	87.86	A75/ 98.57	A75#
TCI/ $CeSi_2$	175.03	295.72	FED/41.40	99.04
$CeSi_2$/ YSZ	172.23	310.31	4.37 / 35.88/ 79 & 98.5-246/ FED	96.78
YSZ/ work.medium	690	771.36	590	648.07

A – only the fluid or air temperature (convection), # - the temperatures at the injection jet upon request, FED – can or should be FEM-defined, .../.../...&.../... – the first number denotes temperature from shortened integral equation with radiation, the next ones being proposals – about blank area/range between the conduction phonon solution and those including radiation – see the Conclusions. This is valid for Tab.2-5.

Tab. 3. The interface temperatures, the 2-type; ^{o} C

Interface	Pt.1	Pt.2	Pt.3	Pt.4
Air/ TCI	A75	84.27	A75	A75#
TCI/ $CeSi_2$	98.96	218.83	FED/ 80.10	28.89/ FED
$CeSi_2$/ enstatite	95.38	233.40	FED/ 77.14	28.47/ FED
Enstatite/ YSZ	170.52	313.17	6.39/ 81 & 147 & 98.5-246/ FED	99.11/FED
YSZ/ medium	690	771.36	590	648.07

Tab. 4. The interface temperatures, the 3-type; ^{o} C

Interface	Pt.1	Pt.2	Pt.3	Pt.4
air/TCI	98.90	82.22	98.89	75.95#
TCI/composite	206.58	193.03	196.74	178.94
composite/medium	690	771.36	590	648.07

Tab. 5. The interface temperatures, the 4-type; ^{o} C

Interface	Pt.1	Pt.2	Pt.3	Pt.4
air/TCI	A75	A75	A75	A75
TCI/ PtAu alloy	FED	FED	FED	FED
The PtAu alloy/ plagioclase	133.42	286.07	-1.17/ 74 & 49-280/FED	63.88/ 279/ FED
plagioclaase/medium	690	771.36	590	648.07

Large temperature drops in the 4-model are understood as from reflectivity, but large drops in models including cerium disilicide (even after addition temperatures from the unitary processes) are somewhat improbable and surely being the result of poor working of the radiation including algorithm at medium temperatures (see below). The cerium disilicide itself is of $\lambda = 13$ W/mK, and a bit soluble in water. Several non-logical values being are result of small errors, but in general case, one cannot exclude possibility of similar temperature (say $CeSi_2$/YSZ and $CeSi_2$/TCI interface) in materials of accumulative-radiative properties and several layers (reflectivity). Stresses are computed from the temperatures, but temperatures depend on stresses since material in tension poorly conduct heat – an item seldom appearing in the materials science. Besides, the endothermic transformations or porosity (plagioclase, feldspars) can heavily lower temperature. The plagioclase used in the simulations was of CTE = 11 ppm/K, and the labradore (Ca-rich feldspar) conductivity 'to cover' several minerals. Apart from the temperatures from the tables, those computed for the faying surfaces were added: 758.02, 758.02, 238.63 and 165.48 ^{o} C. In the 3- and 4 points of the Tab.2, 3 and 5, the 246, 147 and 133.5^{o} C were assumed at the respective interfaces (where the proposals). The temperatures from the nook and corners of the cylinder head were not used in simulation - to check the results – those are not bed – Tab.6. The range and most interesting points of the cylinder head are presented below – Tab.7.

Tab. 6. Comparison of temperatures in definite points of the head by FEM (ANSYS12, 13) and FDM (FORTRAN 9, ^{o}C

FEM	FDM	Locality
371.51 (close to)	344.0366	The exhaust-valve-pin-liner entrance
378.51	411.8303	Point/the outer face of the exhaust pipe
64.23-142.8	98.9047	Cavity/recess at the exhaust pipe (above the cylinder liner)
64.23-142.8	75.9451 98.8873 93.3679	Internal head wall at the intake valve (above the cylinder liner)

Tab. 7. The range and the interesting points of stresses in the cylinder head (MPa)

Model /type No.	4	3	2	1
The first principal, S1	-53 0.77c, +826.899w -78.214/72.538ż	+341.266b, - 41.216/+43.734	+465.782c, - 64.645/+53.288, pkt. +230.037,+ 288.573	+525.614b, -71.733/+61.011ż
The second principal, S2	+322.507w, -1368b -428.841/-241.004fp -241./-53.167ptau	- 381.197żm,211.247ż/c -117.899/+13.766ż, -249.543/+13.766 b	-558.105bc, c, +328b, -65/+33ż	-559.21b, +311.466b -75.501/+21.241ż
The third principal, S3	-584.876c, -2926b, +83.898max	-1239ż, - 405.404/+11.288b	-1608ż,c -698/+29c	-1609/-12.53żc, -899b, -367b
The XZ shear, SXZ	-234.711/-427.555b - 41.867/+150.997ż - 813.242/+922.352w	~0	~0	~0
The YZ shear, SYZ	-39.743/+47.709 - 389.553/+397.519w	~0	~0	~0
the XY shear, SXY	-393.429/+50.708b, +139.535b, +406.017max	-188.561/+167.283 faying surface	- 187.566/+183.73pbc , - 146.302/+101.222c	- 182.49+161.862pbc, -29.444/+8.817ż
Von Mises'*	<650/5.812c, 328.176c/m, 1200b	38/1169	51.806/1480	-

c – stands for TBC ceramics or composite, b – boundary ceramis/TCI or compositeTCI (without interlayer), ż – TCI, w –in proximity of the inject jet, żm – TCI between valves, fp –feldspar (plagioclase), ptau – the PtAu alloy, bc – the boundary and the ceramics (composite), żc – TCI and the ceramics [not the boundary], max – the tension max., pbc – the faying surface close to the ceramics, but not the boundary, c/m – composite/the PtAu alloy boundary; blank – the range [TCI, frequently], * - of no information value, ż/c – TCI/the ceramics boundary.

One can see that maximum value of temperature are about 690°C at the intake jet (Fig.1).

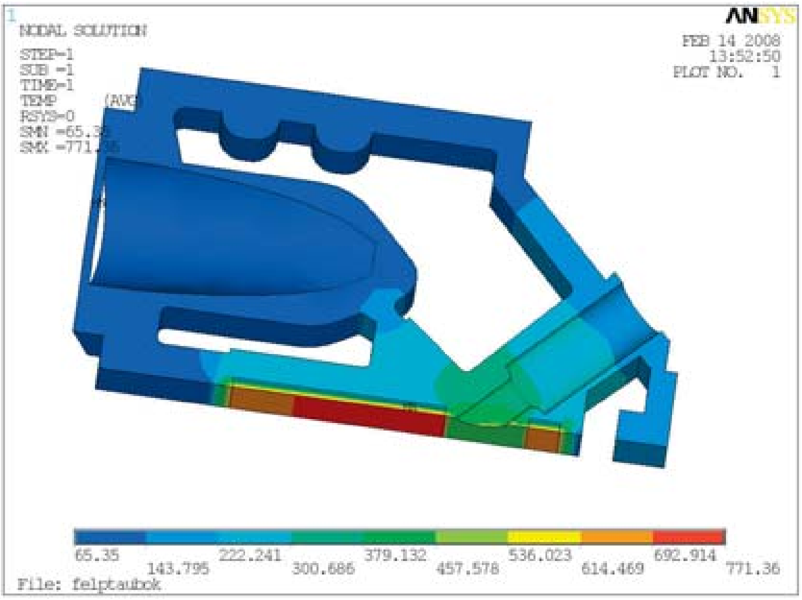

Fig. 1. The 4-model; the temperature field of cylinder head

Fig.2 presents stresses field in cylinder heat with ceramics in proximity of the intake duct and joint cast iron and ceramic. Maximum value of stresses are about 670 MPa in the intake duct.

The stress field in the cylinder head with boundary ceramic and cast iron in proximity of the intake duct, feldspar and the PtAu alloy is presented in Fig.3. One can see that maximum value of stresses and temperature gradients in the cast iron-feldspar boundary is at the end of the intake duct.

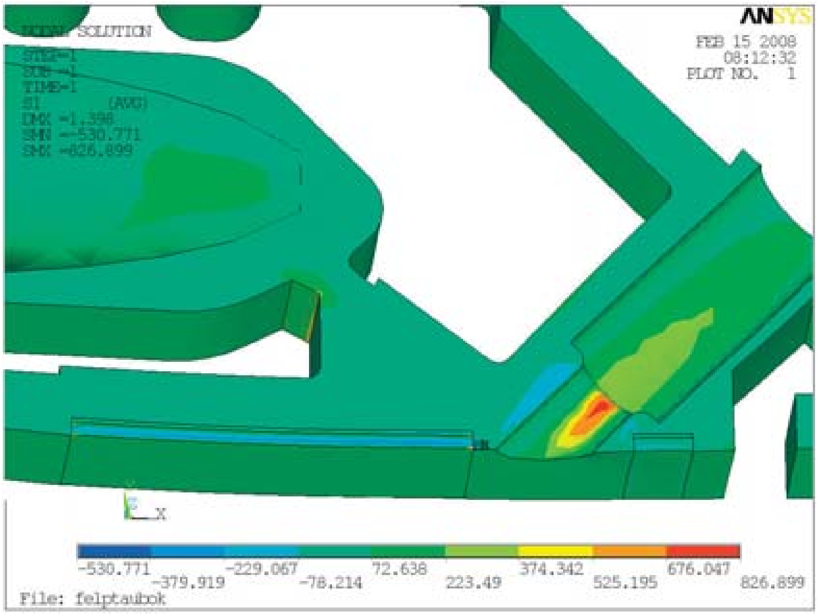

Fig. 2. The 4-model; the first principal, the stresses field of cylinder head - tabl.7

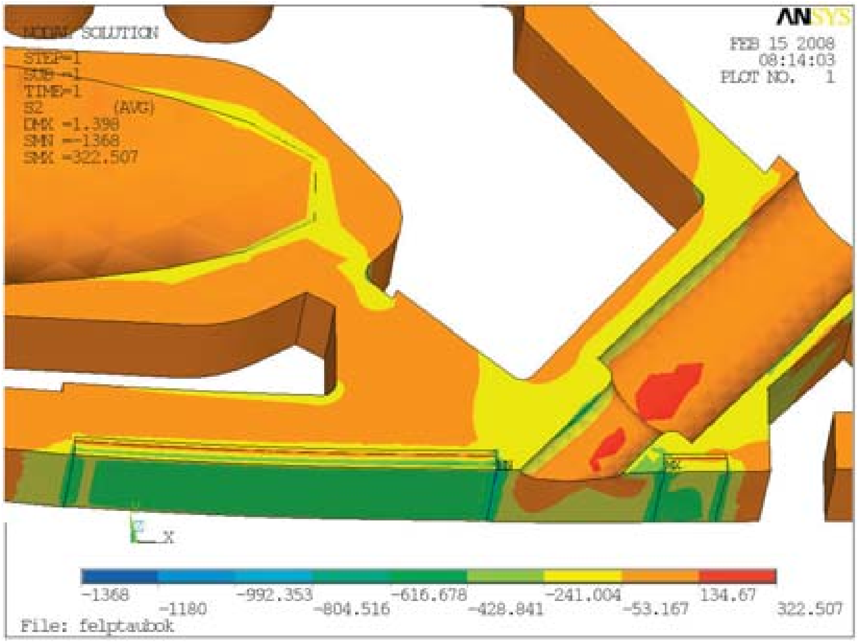

Fig. 3. The 4-model; the second principal , the stresses field of cylinder head – tabl.7

Fig.4 shows the maximum of shear stresses at the cast iron-feldsper boundary (without the alloy) reaching value +922 MPa.

Though the real thermal (residual) stresses should be lower due to diverse causes, and, the experiment proves necessary as regards strengths of joints, it turns out that the crystal chemical approach gave some reasonable results (though the FEM-stresses are averaged) and that there in the structure, it is rather not ceramics, but the cast iron that will not withstand (acc. to FEM). It should be replaced by a more Mo-Cr cast iron, composite, plated or wholly covered by ceramics at the injection jet.

3. Conclusion

Ceramics per se can be avoided at 'intervalve point' and the exhaust pipe should be covered by a TBC. Excepting the pipe, the head should be deemed 'quite cold'. One can divide models into the best ones (Nos.3, 4, especially 3) and the worst ones (Nos. 1 and 2, 1 especially). It does not matter that plagioclase (and the related), the pyroxene and $CeSi_2$ are of lower melting temperature than YSZ does – they are already far from the average temperature of the working medium, and comparable with steels.

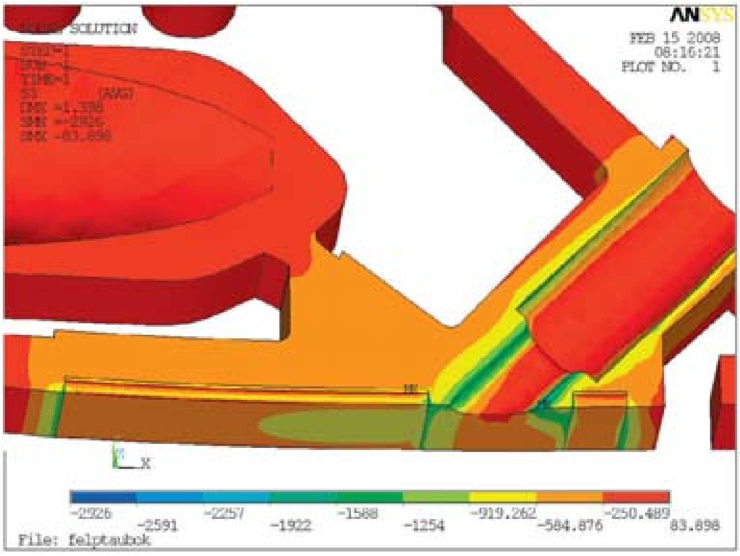

Fig. 4. The 4-model; the third principal, the stresses field of cylinder head – tabl.7

Moreover, weathered plagioclase can display böhmite, γ-AlOOH structure on the surface, emissivity of which should be very low. It is not the case at YSZ, but it can be covered, e.g. by rutile. Though only a few data are in the authors' disposal to use plastic-elastic theories, the plagioclase, pyroxene and cerium disilicide can be deemed more or less reliable in those structures. This is not valid at YSZ or TCI. It is not only of high E, but also, perhaps, of low compressivity [3]. Finally, if one uses CTE dropping in the direction from metal to the ceramics, so as to the metal being hoop for ceramics – it will be natural using a metal of the high plastic limit. It also appears that there is some blank area/range of the temperature computation between the results of the radiation-including algorithm and that based on phonons. Several/many materials draw theirs 'radiation-deflection point' to quite low temperatures – and the above algorithm is too steep, whereas the phonon computations are methodologically incorrect, i.e. above the deflection point.

References

[1] Grasselly, G., *An attempt to characterize the stability relations of tetrahedral oxidations by their complex anionic potentials*, N. Jb. Miner., Abh. (Festband Ramdohr), p.1075-1092, 1960.

[2] Kwaśniowski, S., Sroka, Z. J., Zabłocki, W., *Modelowanie obciążeń cieplnych w elementach silników spalinowych*, Oficyna Wydawnicza Polit. Wrocławskiej, Wroclaw, 1999.

[3] Ramberg, H., *Artificial and natural photoelastic effects in quartz and feldspars*, Amer. Miner., p. 934-951, 1961.

[4] Samsonov, G. V., Dvorina, L. A., Rud, B. M., *Silicidy*, Metallurgia, Moskva, 1979.

[5] Woods, M. E., Mandler, Jr. W. F., Scofield, T. L., *Designing ceramic insulated components for the adiabatic engine,* Ceramic Bull., p.287-289 and 292-293, 1985.