Norwegian University of Science and Technology
Department of Energy and Process Engineering

Contact during exam:
Ivar S. Ertesvåg, phone (735)93839

EXAM IN SUBJECT TEP4170 HEAT AND COMBUSTION TECHNOLOGY
(Varme- og forbrenningsteknikk)
25 May 2016 Time: 0900 – 1300

The exam is only available in English. The answers can be written in Norwegian or English.

Permitted aids: D – No printed or handwritten aids. Certain simple calculator.

- Please do not use red pencil/pen, as this is reserved for the censors.
- Read through the problems first. Begin with the problem where you feel that you have the best insight. If possible, do not leave any problems blank. Formulate clearly, it pays off!
- Some information is given at the end.

Problems:

1)
The momentum equation (“basic”, “instantaneous”) can be formulated as

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij}\right) + \rho f_i$$

--Develop the equation for mean (Reynolds average) momentum.
--Which information is lost in this operation?

New quantities appear in the new equation, known as Reynolds stresses.
--What is the interpretation/significance of these terms?

Norwegian: momentum = “rørslemengd”/”bevegelsesmengde”

2)
Reynolds stresses can be found from the k-ε model. The quantities k and ε are determined from modeled equations.
--Put up the necessary expressions to determine the Reynolds stresses when k and ε are known. Define the symbols/quantities involved.

Note: You are not asked to put up or develop the equations for k and ε.

In a similar development for the mean species mass equations, the Reynolds fluxes appear.
--Put up the necessary expressions to determine the Reynolds fluxes based on the k-ε model. Define the (additional) symbols/quantities involved.

3)
For a turbulent boundary layer, the following expression can be found:

$$u_1^+ = \min\left(x_2^+, \frac{1}{\kappa}\ln x_2^+ + C \right)$$

-- Define the quantities involved here.
-- Show how the relation is obtained. Point out the assumptions made during the development.
-- Why – and when – is this relation needed?

4)
--What is a conserved scalar? Give two examples. Point out the relevant conditions/assumptions required for these two examples.

--Define the mixture fraction. (Norw: “blandingsfraksjon”)

--Determine the value of the stoichiometric mixture fraction for propane (C_3H_8) burned with air (21% O_2, 79% N_2 molar based)

5)
Oxidation of CO can (on certain conditions) be described by the following reactions:

$CO + O_2 \rightarrow CO_2 + O$, (CO.1)
$O + H_2O \rightarrow OH + OH$, (CO.2)
$CO + OH \rightarrow CO_2 + H$, (CO.3)
$H + O_2 \rightarrow OH + O$, (CO.4)

The forward and reverse (backward) reaction rate coefficients, k_f and k_r, can be assumed known for each reaction.

--Express the reaction rate of OH based on these reactions.

--One of these reactions can be suspected to be slower than the others. Which one, and why?

6)
--Sketch the Borghi diagram for turbulent premixed flames.
Include lines for constant Re_T, Da, Da_K, $u' = u_\mathrm{L}$ and indicate the direction of increase of these quantities. Define all quantities involved/used.

--Locate the regimes of “wrinkled flames”, “thick flames” and “laminar flames” in the sketched diagram. (Norw.: “rukkete flamer”, “tjukke flammer” og “laminære flammer”)

7)
The Eddy Dissipation Concept (EDC):
--What are the main parts of the model and what is/are the purpose(s) of each part.

--When EDC is used, what other models are needed in the complete set of models for a CFD simulation of a turbulent flame.

8)
In EDC, the mean reaction rate is modeled as $\overline{R}_k = -\frac{\overline{\rho}\dot{m}\chi}{1-\gamma^*\chi}(\tilde{Y}_k - Y_k^*)$

--Show the development of this relation. Define all quantities involved.

The following relation is given and need not be shown or justified here: $(Y_k^o - Y_k^*) = \frac{(\tilde{Y}_k - Y_k^*)}{1-\gamma^*\chi}$

9)
The exhaust of a gas turbine fueled by methane (CH_4) is investigated.
Measurements show a content (molar based) of 20 ppm NOx and 13% O_2 at "wet" conditions.
--What is the NOx content (ppm) at "dry" conditions?
--Correct the concentration of NOx to 15% O_2 (at "wet" conditions).
--Determine the emission index (EI) for NOx, assuming that all NOx is NO.
--Determine the emitted mass of NOx (assumed as NO) per unit of fuel energy (lower heating value).

The oxidizer is air, which can be assumed as 21% O_2, 79% N_2, molar based.

10)
Exhaust gas recirculation (EGR, aka. flue gas recirculation) is used as a means to reduce NOx emissions.
--Explain why EGR can reduce NOx

<u>Information:</u>

Molar masses (kg/kmol), C_3H_8: 44; CH4: 16; CO_2: 44; H_2O: 18; O_2: 32, N_2:28, NO: 30
Lower heating value, (LHV) of methane: 50 MJ/kg