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Department of Energy and Process Engineering

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EXAM IN SUBJECT TEP4170
HEAT AND COMBUSTION TECHNOLOGY
(Varme- og forbrenningsteknikk)
4 June 2010 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!

NOTE: The decimal sign is comma.

Problems:

1)

The equation for the turbulence energy can be written as

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k \bar{u}_j) = \frac{\partial}{\partial x_j}(\mu \frac{\partial k}{\partial x_j}) + \frac{\partial}{\partial x_j}(-\frac{1}{2} \overline{\rho u'_i u'_i u'_j} - \overline{p' u'_j}) - \overline{\rho u'_i u'_j} \frac{\partial \bar{u}_i}{\partial x_j} - \mu \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_i}{\partial x_j}$$

- This equation is called “exact”, why?
- Mention the assumptions made to develop this equation.
- Show how this equation can be developed (the principle, not every detail).
- What is the interpretation of each of the six terms in the equation?

2)

-- Write the modelled k and ε equations as they are used in the “standard” k - ε model.

3)

In some instances we use wall functions (Norw: “vegglover”, “veggfunksjonar”).

-- What is a “wall function” and why do we use it?

-- Develop the wall function for ε

Hint: on certain assumptions/conditions (and with the symbols of the textbook), $\frac{\partial \bar{u}_1}{\partial x_2} \approx \frac{u_\tau}{\kappa x_2}$

4)

In isotropic decaying turbulence (Norw: "isotrop minkande turbulens") it is found from experiments that the turbulence energy develops as

$$k(t) \sim t^{-n}, \text{ where } n \text{ is positive } (1 < n < 1,5) \text{ and } t \text{ is time}$$

-- Determine the corresponding form of $\varepsilon(t)$.

A length scale l and a Reynolds number Re_T can be expressed from k and ε .

-- How will these quantities develop in isotropic decaying turbulence. Explain the results.

5)

Consider a fully developed turbulent flow in a pipe (Norw: røyr) with smooth (Norw: glatt) inner wall. The inner radius is R .

-- Make sketches (Norw: skisser) of the profiles across the pipe from $-R$ to $+R$ of

- the Reynolds (turbulence) shear stress (Norw: turbulens-skjerspenning),
- the Reynolds normal stress directed along the flow direction,
- the Reynolds normal stress directed normal to the wall, and
- the turbulence energy.

In particular, make sure that values at the wall and at the centerline, the maximum and minimum values and symmetry properties are qualitatively correct. If necessary, use words to state that a quantity is, for instance, zero at the wall.

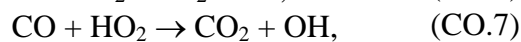
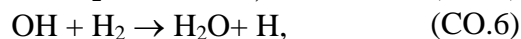
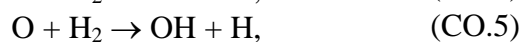
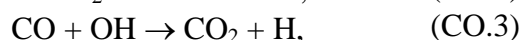
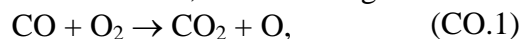
6)

-- What are the differences between and the relations between "global" (overall) reactions and elementary reactions.

-- What are the practical implications of the so-called simplified chemical kinetics mechanisms, and why are they widely used?

7)

From a chemical mechanisms, the following is extracted:



-- Explain the terms chain reaction, chain-initiation reaction, chain-propagating reaction, and chain-termination reaction.

-- To which of these categories does each of the 7 CO-reactions above belong?

8)

-- List and discuss the four steps involved in soot formation and destruction in laminar diffusion (non-premixed) flames.

-- Sketch a typical radial temperature profile and soot concentration profile in a vertical jet of non-premixed hydrocarbon laminar flames.

9)

Two different types of turbulence combustion models are Magnussen's "Eddy Dissipation" model and models based on a prescribed probability density function (Norw: føreskriven sannsynstettleik), also called flamelet models.

-- What are the differences between these models with respect to equations that are solved (that is, "transport" or partial differential equations), how to find mean values (averages, moments), and assumptions that has to be made

10)

A diesel engine fueled with pure n-heptane (C_7H_{16}) is run in an engine dynamometer (testing device). The rate of work (brake power) is 90 kW and the NO analyzer measures 200 ppm NO on a dry basis. The (brake) thermal efficiency of the engine at this load is 40% and the excess air ratio λ is 1.4.

-- Express the NO emissions as:

- Emission Index (EI_{NO} , g NO / kg fuel)
- Mass Specific Emission (MSE_{NO} , g NO / kWh engine work)
- Mass Specific Emission based on fuel energy (g NO / MJ fuel energy)

The emissions of CO and unburned hydrocarbons can be neglected. Air can be assumed as 21% O_2 and 79% N_2 .

-- What is the purpose of expressing the emissions as mass specific or energy specific values?

Lower heating value (LHV), n-heptane :	44.5 MJ/kg (Norw: nedre brennverdi)
Molar mass (mole weight), n-heptane:	100.21 g/mol
Molar mass, NO:	30.01 g/mol

11)

-- What are the main steps of solid fuels (coal and biomass) combustion?

-- What are the simplified film models for carbon combustion? What are the differences between these models?

12)

Given Table 25.1 (p.4), calculate the time needed for complete combustion of a graphite particle (with radius $R_o = 5$ mm; $\rho_B = 2.2$ g/cm³; $k'' = 20$ cm/sec.) in an 8% oxygen stream, assuming that film diffusion does not give any resistance.

The reaction temperature is 900 °C. Molar mass for carbon: 12 g/mol.

Notice that in the table, ρ_B is measured in mol/cm³.

Table 25.1 Conversion-Time Expressions for Various Shapes of Particles, Shrinking-Core Model

	Film Diffusion Controls	Ash Diffusion Controls	Reaction Controls
Flat plate $X_B = 1 - \frac{1}{L}$ $L =$ half thickness	$\frac{t}{\tau} = X_B$	$\frac{t}{\tau} = X_B^2$	$\frac{t}{\tau} = X_B$
	$\tau = \frac{\rho_B L}{bk_g C_{Ag}}$	$\tau = \frac{\rho_B L^2}{2b\mathcal{D}_e C_{Ag}}$	$\tau = \frac{\rho_B L}{bk'' C_{Ag}}$
Cylinder $X_B = 1 - \left(\frac{r_c}{R}\right)^2$	$\frac{t}{\tau} = X_B$	$\frac{t}{\tau} = X_B + (1 - X_B) \ln(1 - X_B)$	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/2}$
	$\tau = \frac{\rho_B R}{2bk_g C_{Ag}}$	$\tau = \frac{\rho_B R^2}{4b\mathcal{D}_e C_{Ag}}$	$\tau = \frac{\rho_B R}{bk'' C_{Ag}}$
Sphere $X_B = 1 - \left(\frac{r_c}{R}\right)^3$	$\frac{t}{\tau} = X_B$	(11) $\frac{t}{\tau} = 1 - 3(1 - X_B)^{2/3} + 2(1 - X_B)$	(18) $\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$ (23)
	$\tau = \frac{\rho_B R}{3bk_g C_{Ag}}$	(10) $\tau = \frac{\rho_B R^2}{6b\mathcal{D}_e C_{Ag}}$	(17) $\tau = \frac{\rho_B R}{bk'' C_{Ag}}$ (22)
Small particle Stokes regime	$\frac{t}{\tau} = 1 - (1 - X_B)^{2/3}$	(30)	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$
	$\tau = \frac{\rho_B R_0^2}{2b\mathcal{D}_e C_{Ag}}$	(29)	$\tau = \frac{\rho_B R_0}{bk'' C_{Ag}}$
Large particle ($u =$ constant)	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/2}$	(31)	$\frac{t}{\tau} = 1 - (1 - X_B)^{1/3}$
	$\tau = (\text{const}) \frac{R_0^{3/2}}{C_{Ag}}$	Not applicable	$\tau = \frac{\rho_B R}{bk'' C_{Ag}}$

Constant Size Particles

Shrinking Sphere

Table 25.1 from Levenspiel