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EXAM IN TEP4170 HEAT AND COMBUSTION TECHNOLOGY
(Varme- og forbrenningsteknikk)
31 May 2024 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!

Problems:
1)
The “exact” equation for turbulence energy, $k=\frac{1}{2}\overline{u_i'u_i'}$, can be written as

$$\underbrace{\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_j}(\rho k\overline{u}_j)}_{\rho C_k}=\underbrace{-\rho\overline{u_i'u_j'}\frac{\partial\overline{u}_i}{\partial x_j}}_{\rho P_k}+\underbrace{\frac{\partial}{\partial x_j}\left(\mu\frac{\partial k}{\partial x_j}\right)}_{\rho D_{k,\mathrm{v}}}$$
$$+\underbrace{\frac{\partial}{\partial x_j}\left(-\tfrac{1}{2}\rho\overline{u_i'u_i'u_j'}-\overline{p'u_j'}\right)}_{\rho D_{k,\mathrm{t}}}-\underbrace{\mu\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}}}_{\rho\varepsilon}. \qquad (3.4)$$

Some of the terms in this equation are expressed from quantities that are already available, while some are not and have to be modelled.

--Which terms have to be modelled, and how are these modelled in
a) a model with only one turbulence equation (i.e. for *k*)?
b) the (standard) $k-\varepsilon$ model?
Define the quantities that you introduce.

2)
Define homogeneous turbulence and isotropic turbulence.

Write the “exact” equation for turbulence energy (see the problem above) for these two instances.

3)
-- Define the mixture fraction.
-- For propane, C_3H_8, burning with air (21% O_2, 79% N_2, molar based), determine the stoichiometric mixture fraction.
Assume an infinitely fast reaction of propane and air, express the mass fractions of propane, air and product as functions of the mixture fraction.

Information: Molar mass (kg/kmol): C_3H_8: 44; O_2: 32; N_2: 28.

4)
In the Eddy Dissipation Concept, the mean reaction rate $\overline{R}_k$ is expressed.
In the development of the expression, an intermediate expression appears as

$$R_k^* = -\rho^* \dot{m}^* (Y_k^o - Y_k^*)$$

-- Describe the underlying idea and how this expression is developed. What do the symbols denote?

The further development leads to

$$\overline{R}_k = -\frac{\rho^* \dot{m}^* \gamma^* \chi}{1-\gamma^* \chi}(\tilde{Y}_k - Y_k^*)$$

-- What are the assumptions leading to this expression? Show how the expression can be obtained.

5)
Assume that combustion can be represented by a single-step global reaction that is infinitely fast.
– Show how the expression for $\overline{R}_k$ given in Problem 4 can be simplified.

6)
The collision theory can be used to predict the rates of chemical reactions. The collision theory states that for a reaction to occur, the molecules must collide with sufficient energy and with a correct orientation.

-- How does a change in the following conditions change the rate of the reaction with respect to the collision theory?

- concentrations of reactants
- temperature
- pressure
- the presence of a catalyst

-- Write the Arrhenius form for the bimolecular rate coefficient, *k(T*), and relate the constants *A* and E_A to the collision theory.

7)
The following two-step mechanism is proposed for the conversion of ozone (O_3) to oxygen (O_2):

1) $O_3 \underset{k_{r,1}}{\overset{k_{f,1}}{\Leftrightarrow}} O_2 + O$, which is assumed to be fast and reversible
2) $O + O_3 \overset{k_2}{\rightarrow} O_2 + O_2$, which is slow

-- Express the reaction rate for each of the reactions (including the reverse reaction).
-- What are the reaction orders of the reactions?
-- Express the reaction rate of O_3 ($d[O_3]/dt$) from this mechanism.

Since the first step is fast and reversible, and the second is slow, we can apply partial equilibrium for the first step.
-- Use partial equilibrium for the first step to simplify $d[O_3]/dt$.

8)
The flame speed of a laminar premixed flame can be determined experimentally using a Bunsen burner.

-- Make a sketch that illustrates how the laminar flame speed can be found in the Bunsen-burner experiment.
-- What quantities do we measure, and what is the mathematical relation(s) between the flame speed and the measured quantities?

-- How can the laminar flame speed be determined for a non-premixed flame?

9)
Assume that a petrol (gasoline) car uses 5.0 L (litre) of fuel per 100 km. For simplicity, the fuel can be represented by octane, C_8H_{18}.
The following ("wet") mole fractions are recorded in the exhaust:
CO_2: 0.125; H_2O: 0.141; O_2: 5 ppm; NO: 16 ppm; CO: 25 ppm.
Unburned hydrocarbons and other minor species can be neglected.
Air can be assumed as 21% O_2, 79% N_2, molar based.
The fuel/air mixture is stoichiometric (i.e. $\lambda = \varphi^{-1} = 1$, 100% theoretical air)

-- Calculate the NO emission index.
-- Calculate the specific emissions in terms of the emitted mass of NOx (assumed as NO) per km.
-- What is the mole fraction of NO on a dry basis?

Molar masses (kg/kmol): C_8H_{18}: 114; CO: 28; CO_2: 44; H_2O: 18; O_2: 32; N_2: 28; NO: 30
Density of C_8H_{18}: 700 kg/m^3 (700 g/L)

10)
Regulations on NOx emissions from diesel-engine cars are becoming stricter, and emissions have to be reduced.
-- Describe one*) strategy limiting the formation of NOx inside the engine cylinder
-- Describe one*) strategy for reducing the NOx in the exhaust.

*) If you describe more than one, the first will be credited, not the following (make clear that you want to omit the first, e.g. by crossing out, if you decide to describe another).