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)
16 May 2017 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 mean momentum equation includes the turbulence stress (Reynolds stress), $-\rho\overline{u_1' u_2'}$.

--Show the development of Prandtl's mixing length model for this quantity.

--How is the turbulence viscosity formulated for this model?

2)

In a zone near a plane wall, the approximation $\frac{d\bar{u}_1}{dx_2} = \frac{u_\tau}{\kappa x_2}$ is used.

-- Define the quantities used.

-- Demonstrate how to express a wall function for the dissipation rate of turbulence energy, ε, from this relation. Explain the additional assumptions that are required.

-- Show how to achieve the expression $\nu_\mathrm{t} = \kappa u_\tau x_2$

3)

In a boundary layer, the temperature function ("law of the wall") is expressed as

$$T^+ = \frac{1}{\kappa_T} \ln x_2^+ + C_T ,$$

where the nondimensional temperature is defined as $T^+ = \rho C_p (T_\mathrm{w} - \bar{T}) u_\tau / q_\mathrm{w}$

-- Show how to develop this expression. (Hint: the previous problem)

4)

Transported multidimensional joint pdf ("transported pdf") is a method for modeling turbulent reacting flow.

--Describe the ideas of this method, including

- -- for which quantities equations have to be formulated and solved,
- -- which terms (phenomena) that have to be modeled, and which phenomena need no further modeling in these equations,
- -- how averages (e.g. average temperature) are expressed with this method.

5)
Under some assumptions, the mixture fraction (Norw: “blandingsfraksjon”) can be a characteristic variable, from which other variables can be expressed.
--For methane combustion in air, express the mass fractions of CH_4, CO_2 and O_2 as functions of the mixture fraction.

The stoichiometric air (theoretical air) is 17,1 kg per kg methane. You can assume that air is 23,3% O_2 and 76,7% N_2 (mass based), the reaction is infinitely fast, complete and irreversible.
Molar masses (kg/kmol): CH_4: 16; CO_2: 44; H_2O: 18; O_2: 32; N_2: 28

6)
Assume that you have found the mass fractions and temperature as functions of the mixture fraction, $Y_i(\xi)$ and $T(\xi)$ (cf. problem above).
--Describe how you can determine the mean mass fractions $\bar{Y}_i$, the temperature variance $\overline{T'^2}$ from these functions. What are the conditions of validity for these expressions?

7)
A chemical mechanism for hydrogen and oxygen contains the following reactions:

$O_2 + H \rightarrow OH + O$,	(H.1)
$H_2 + O \rightarrow OH + H$,	(H.2)
$OH + H_2 \rightarrow H + H_2O$,	(H.3)
$H_2O + O \rightarrow 2OH$,	(H.4)

The forward reaction rate coefficient is given as a function of temperature, $k_f = k_f(T)$, for each reaction. However, the reverse (backward) reaction rate coefficients k_r, are not given in the dataset of the chemical mechanism.
--Show how the reverse reaction rate coefficient for Reaction H.1 , $k_{r1}(T)$, can be found. Specify which data that are needed.

8)
--Express the reaction rate of OH based on the reactions in Problem 7.
Here, the forward and reverse (backward) reaction rate coefficients, k_f and k_r, can be assumed known for each reaction.

9)
A combustor has a width of 0,1 m × 0,1 m, a length of 0,4 m, an inlet velocity of 10 m/s. The timescales of the reactions ranges from 10^{-6} s to 0,1 s and the length scales from 10^{-5} m to 0,01 m. The kinematic viscosity and diffusivities can be assumed at 10^{-5} m^2/s.

--Estimate the required resolution in time and space for a direct numerical simulation of this case.

10)
The CO in the flue gas from a gas turbine is measured as 25 ppm (volume based, “dry”) at a O_2 content of 13%. The fuel is methane, CH_4.
--Determine the CO emissions in kg CO per kg fuel.

Emission regulations are specified at a 15% O_2 content, dry.
--Determine the CO emissions according to these regulations
Molar masses (kg/kmol): CH_4:16, CO: 28; CO_2: 44; H_2O: 18; O_2: 32; N_2: 28.