NORGES TEKNISK-NATURVITENSKAPELIGE UNIVERSITET
INSTITUTT FOR ENERGI- OG PROSESSTEKNIKK

Faglig kontakt under eksamen:
Førsteamanuensis Kjell Erik Rian, tlf. (735)93094

EKSAMEN I EMNE TEP4170 VARME- OG FORBRENNINGSTEKNIKK
Tirsdag 20.mai 2008
Tid: 09.00 – 13.00

Sensuren faller 11.juni 2008.

Oppgaveteksten finnes også på engelsk.

Hjelpemidler:
D – Ingen trykte eller håndskrevne hjelpemidler tillatt. Bestemt, enkel kalkulator tillatt.

Bruk helst ikke rød blyant/penn, det er forbeholdt sensuren.

Les gjennom oppgavene først. Start med den oppgaven du mener du har best innsikt i. Dersom det er mulig, la ikke noen oppgave være helt blank. Skriv klart, det lønner seg!

Oppgave 1

— Forklar om turbulens ut fra disse stikkordene:
strømning, rom og tid, diffusiv, lengdeskalaer, energioverføring, forbrenning.

Oppgave 2

Likningen for middel-massefraksjonen av et stoff k kan skrives som

$$\frac{\partial}{\partial t}\left(\rho \overline{Y}_k\right) + \frac{\partial}{\partial x_j}\left(\rho \overline{u}_j \overline{Y}_k\right) = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial \overline{Y}_k}{\partial x_j} - \rho \overline{u_j' Y_k'}\right) + \overline{R}_k$$

— Vis hvordan vi kommer fram til denne likningen.
— Hva representerer de ulike leddene i likningen?

Oppgave 3

I et todimensjonalt grensesjikt ved en vegg opptrer korrelasjonen $-\overline{u_2' Y_k'}$, der Y_k er massefraksjon av et stoff k.
— Vis hvordan korrelasjonen $-\overline{u_2' Y_k'}$ kan modelleres ved hjelp av en gradienttransportmodell.
— Hvordan blir den modellerte versjonen av $-\overline{u_2' Y_k'}$ dersom Prandtls blandingsveiteori benyttes for modellering av hastighetsfeltet?

Oppgave 4

En likning for turbulensenergien, k, kan skrives som

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

— Vis hvordan denne likningen kan utledes. (Du trenger ikke å vise alle detaljer for alle ledd.)
— Hvilke ledd i likningen må modelleres?

Oppgave 5

— Forklar én-film-modellen, to-film-modellen og kontinuerlig-film-modellen for karbonforbrenning.
— Skissér stoff- og temperaturprofilene ved bruk av én-film-modellen for karbonforbrenning når en antar at kun CO_2 dannes ved forbrenningen ved karbonoverflaten.

Oppgave 6

Propan (C_3H_8) brennes med luft i en gassbrenner. Følgende molfraksjoner ble målt i eksosgassen under testing: χ_{CO_2}=0,150, χ_{O_2}=0,010 og χ_{H_2O}=0,210.
Utslippet av NO ble målt til 110 ppm.
— Beregn utslippsindeksen for NO (eng.: NO emission index) for gassbrenneren når en kan anta neglisjerbare konsentrasjoner av CO og uforbrente hydrokarboner i eksosgassen. (Molvektene til C_3H_8, CO_2, O_2, H_2O og NO er respektivt 44, 44, 32, 18 og 30 kg/kmol.)
— Hva er hensikten med å korrigere konsentrasjonene til et gitt O_2-nivå i eksosgassen ved rapportering av utslipp fra forbrenningsprosesser?

Oppgave 7

Dannelse av termisk NO kan beskrives ved mekanismen

$$\mathrm{N_2 + O} \underset{k_{1,\mathrm{b}}}{\overset{k_{1,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + N}$$

$$\mathrm{N + O_2} \underset{k_{2,\mathrm{b}}}{\overset{k_{2,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + O}$$

$$\mathrm{N + OH} \underset{k_{3,\mathrm{b}}}{\overset{k_{3,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + H,}$$

der

$$
\begin{aligned}
k_{1,\mathrm{f}} &= 1,8 \cdot 10^{8} \cdot e^{-38370/T}\,\mathrm{m^3 mol^{-1} s^{-1}} \\
k_{1,\mathrm{b}} &= 3,8 \cdot 10^{7} \cdot e^{-425/T}\,\mathrm{m^3 mol^{-1} s^{-1}} \\
k_{2,\mathrm{f}} &= 1,8 \cdot 10^{4}\, T \cdot e^{-4680/T}\,\mathrm{m^3 mol^{-1} s^{-1}} \\
k_{2,\mathrm{b}} &= 3,8 \cdot 10^{3}\, T \cdot e^{-20820/T}\,\mathrm{m^3 mol^{-1} s^{-1}} \\
k_{3,\mathrm{f}} &= 7,1 \cdot 10^{7} \cdot e^{-450/T}\,\mathrm{m^3 mol^{-1} s^{-1}} \\
k_{3,\mathrm{b}} &= 1,7 \cdot 10^{8} \cdot e^{-24560/T}\,\mathrm{m^3 mol^{-1} s^{-1}}.
\end{aligned}
$$

— Formulér uttrykk for $\frac{d[\mathrm{N}]}{dt}$ og $\frac{d[\mathrm{NO}]}{dt}$.
— Hvilken reaksjon er den hastighetsbestemmende reaksjonen i dannelsen av termisk NO? Forklar hvorfor reaksjonen er hastighetsbestemmende.

Oppgave 8

— Vis at Zeldovich-mekanismen for dannelse av NO kan reduseres til

$$\frac{\mathrm{d[NO]}}{\mathrm{d}t} = 2k[\mathrm{N_2}][\mathrm{O}],$$

der k er reaksjonskonstanten for den hastighetsbestemmende reaksjonen.
Hvilke antagelser må du gjøre?

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
DEPARTMENT OF ENERGY AND PROCESS ENGINEERING

Contact during examination:
Associate Professor Kjell Erik Rian, tel. (735)93094

EXAM IN SUBJECT TEP4170 HEAT AND COMBUSTION TECHNOLOGY
Tuesday 20 May 2008
Time: 09.00 – 13.00

Examination results are published: 11 June 2008.

This exam is also available in Norwegian.

Permitted aids:
D – No printed or handwritten aids. Approved calculator.

Please do not use a red pencil/pen, 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 problem blank. Formulate clearly, it pays off!

Problem 1

— Explain about turbulence from the following key words:
flow, space and time, diffusive, length scales, energy transfer, combustion.

Problem 2

The equation for the mean mass fraction of species k can be written as

$$\frac{\partial}{\partial t}\left(\rho \overline{Y}_k\right) + \frac{\partial}{\partial x_j}\left(\rho \overline{u}_j \overline{Y}_k\right) = \frac{\partial}{\partial x_j}\left(\rho D \frac{\partial \overline{Y}_k}{\partial x_j} - \rho \overline{u_j' Y_k'}\right) + \overline{R}_k$$

— Show how this equation is derived.
— What do the various terms in this equation represent?

Problem 3

In a two-dimensional wall boundary layer the correlation $-\overline{u_2' Y_k'}$ appears, where Y_k is the mass fraction of species k.
— Show how the correlation $-\overline{u_2' Y_k'}$ can be modelled by assuming a gradient-transport model.
— How will the modelled version of $-\overline{u_2' Y_k'}$ become if Prandtl's mixing-length theory is used to model the velocity field?

Problem 4

An equation for the turbulence energy, k, can be stated as

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

— Show how this equation can be derived. (You don't have to show all the details for all the terms.)
— Which terms in the equation have to be modelled?

Problem 5

— Explain the one-film model, the two-film model, and the continuous-film model for the burning of carbon.
— Sketch the species and temperature profiles for the one-film model of carbon combustion assuming that CO_2 is the only product of combustion at the carbon surface.

Problem 6

Propane (C_3H_8) is burned with air in a gas burner. During testing, the following mole fractions were measured in the exhaust gas: χ_{CO_2}=0.150, χ_{O_2}=0.010, and χ_{H_2O}=0.210.
The NO emission level was found to be 110 ppm.
— Calculate the NO emission index for the gas burner when negligible exhaust gas concentrations of CO and unburned hydrocarbons are assumed. (The molecular weights of C_3H_8, CO_2, O_2, H_2O, and NO are 44, 44, 32, 18, and 30 kg/kmol, respectively.)
— What is the purpose of correcting the concentrations to a specific O_2 level in the exhaust gas when reporting emissions from combustion processes?

Problem 7

Formation of thermal NO can be described by the mechanism

$$\mathrm{N_2 + O} \underset{k_{1,\mathrm{b}}}{\overset{k_{1,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + N}$$

$$\mathrm{N + O_2} \underset{k_{2,\mathrm{b}}}{\overset{k_{2,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + O}$$

$$\mathrm{N + OH} \underset{k_{3,\mathrm{b}}}{\overset{k_{3,\mathrm{f}}}{\rightleftharpoons}} \mathrm{NO + H},$$

where

$$\begin{aligned}
k_{1,\mathrm{f}} &= 1.8 \cdot 10^8 \cdot e^{-38370/T}\,\mathrm{m^3mol^{-1}s^{-1}} \\
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\end{aligned}$$

— Formulate expressions for $\frac{d[\mathrm{N}]}{dt}$ and $\frac{d[\mathrm{NO}]}{dt}$.
— Which reaction is the rate-limiting reaction for thermal NO formation? Explain why the reaction is rate limiting.

Problem 8

— Show that the Zeldovich mechanism for NO formation can be reduced to

$$\frac{\mathrm{d[NO]}}{\mathrm{d}t} = 2k[\mathrm{N_2}][\mathrm{O}],$$

where k is the reaction constant for the rate-limiting reaction.
Which assumptions do you need to make?