TEP4170 HEAT AND COMBUSTION TECHNOLOGY Exam 31 May 2024 - Suggested solutions

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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.

The purpose of a model like this is to express mean velocities, meaning that these and their gradients are already included as variables in the problem, together with the density ρ and the viscosity μ. Given that we have put up the k equation, the two terms on the left-hand side (ρC_k) and the 2nd RHS term $(\rho D_{k,v})$ are expressed from available quantities. The first RHS term term (ρP_k) needs to be modelled. The turbulence energy k is used to express the turbulence viscosity, ν_t or $\mu_\mathrm{t} = \rho \nu_\mathrm{t}$, which in turn is used to express the Reynolds stresses, $-\rho \overline{u_i' u_j'}$. This also closes the term ρP_k. The remaining last two terms, $\rho D_{k,t}$ and $\rho\varepsilon$, have to be re-expressed from some of the available quantities.

For <u>a) and b):</u> Reynolds stresses : $-\overline{u_i' u_j'} = \mu_\mathrm{t}\left(\frac{\partial \overline{u}_i}{\partial x_j} + \frac{\partial \overline{u}_j}{\partial x_i}\right) - \frac{2}{3} k \delta_{ij}$ (ρ constant)

a)

Turbulence viscosity, $\mu_\mathrm{t} = \rho C_\mu \sqrt{k} L$; where L is a length scale for turbulence, which has to be specified for the particular configuration; C_μ is a constant.

$$\rho D_{k,t} = \frac{\partial}{\partial x_j}\left(\frac{\mu_\mathrm{t}}{\sigma_k}\frac{\partial k}{\partial x_j}\right)$$

$\rho\varepsilon = \rho C_D k^{3/2} L^{-1}$, where L is the length scale for turbulence used in the turbulence viscosity. C_D is a constant for the model, which has to be specified. One of the constants C_μ and C_D depends on the other.

b)

Turbulence viscosity, $\mu_\mathrm{t} = \rho C_\mu k^2 / \varepsilon$, where C_μ is a constant. For ε, see below.

$\rho D_{k,t}$: same as in a)

ε is solved from its own (modelled) equation (a "transport equation", similar to the k equation).

2)
Define homogeneous turbulence and isotropic turbulence.
Write the “exact” equation for turbulence energy (see the problem above) for these two instances.

Homogeneous turbulence: translatorically invariant; the averaged turbulence quantities (mean values of correlations) do not change when moving in space, i.e. spatial gradients are zero. The mean values of individual quantities, e.g. mean velocity, may have spatial gradients.

$$\frac{\partial}{\partial t}(\rho k) = -\rho\overline{u_i'u_j'}\frac{\partial \overline{u}_i}{\partial x_j} - \mu\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}} \quad \text{or} \quad \frac{\partial}{\partial t}(\rho k) = \rho P_k - \rho\varepsilon$$

Isotropic turbulence: rotationally invariant; the averaged turbulence quantities (mean values of correlations) do not change when rotating the view in space. Implies that spatial gradients are zero (also individual quantities, like mean velocities), that correlations that are not autocorrelations are zero, and that autocorrelations (mean of multiples of a fluctuating quantity, e.g. Reynolds normal stresses) are the same in all directions.

$$\frac{\partial}{\partial t}(\rho k) = -\mu\overline{\frac{\partial u_i'}{\partial x_j}\frac{\partial u_i'}{\partial x_j}} \quad \text{or} \quad \frac{dk}{dt} = -\varepsilon$$

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. Assuming 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.

Mixture fraction: $\xi = \dfrac{\varphi_{\text{mix}} - \varphi_2}{\varphi_1 - \varphi_2}$

Here, φ is a conserved scalar (quantity with zero source term), subscript mix denotes the mixture, and 1 and 2 denote two different inflows to the mixing process.
The mixture fraction is the fraction of mass in the mixture that originates from inlet 1.

Stoichiometric mixture fraction: The expression can be remembered, or it can be developed by using the conserved scalar $(Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})$ for a process where inlet 1 is fuel $(Y_{\text{fu}} = 1,\ Y_{\text{ox}} = 0)$ and inlet 2 is oxidizer $(Y_{\text{fu}} = 0,\ Y_{\text{ox}} = 1)$. r is the stoichiometric amount of oxidizer on mass basis:

$$\xi_{\text{st}} = \frac{(Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})_{\text{st}} - (Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})_2}{(Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})_1 - (Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})_2} = \frac{0-(0-\frac{1}{r}\cdot 1)}{(1-0)-(0-\frac{1}{r}\cdot 1)} = \frac{1}{r+1}$$

For propane, the stoichiometric reaction is $\mathrm{C_3H_8} + 5(\mathrm{O_2} + \frac{79}{21}\mathrm{N_2}) \rightarrow 3\mathrm{CO_2} + 4\mathrm{H_2O} + 18.81\mathrm{N_2}$

$$r = \left(\frac{m_{\text{ox}}}{m_{\text{fu}}}\right)_{\text{st}} = \frac{5(M_{\mathrm{O_2}} + \frac{79}{21}M_{\mathrm{N_2}})}{M_{\mathrm{C_3H_8}}} = \frac{5(32 + \frac{79}{21}\cdot 28)\ \text{kg/kmol}}{44\ \text{kg/kmol}} = 15{,}6\ \text{kg/kg}$$

$$\xi_{\text{st}} = \frac{1}{15{,}6+1} = \underline{0{,}060}$$

From the definition of ξ, and using $(Y_{\text{fu}} - \frac{1}{r}Y_{\text{ox}})$ as the conserved scalar, noting that with an infinitely fast reaction, the fuel rich mixture $(\xi_{\text{st}} \le \xi \le 1)$ has zero oxidizer, and for the fuel lean mixture $0 \le \xi \le \xi_{\text{st}}$ has zero fuel:

$$Y_{\mathrm{ox}}(\xi)=0\ ; \qquad Y_{\mathrm{fu}}(\xi)=\frac{\xi-\xi_{\mathrm{st}}}{1-\xi_{\mathrm{st}}}=\frac{1}{r}((1+r)\xi-1) \text{ for } \xi_{\mathrm{st}}\le\xi\le 1$$

$$Y_{\mathrm{ox}}(\xi)=1-\frac{\xi}{\xi_{st}}=1-(1+r)\xi\ ;\ Y_{\mathrm{fu}}(\xi)=0 \qquad \text{for } 0\le\xi\le\xi_{\mathrm{st}}$$

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.

The underlying idea is that reactions occur in the “fine structures” or small eddies, and that these can be modeled as an open, well mixed (aka. homogeneous) reactor. The reaction rate of species *k* comes from the species mass balance for this reactor,

$$\dot{M}_{\mathrm{in}}Y_k^o-\dot{M}_{\mathrm{out}}Y_k^*=-R_k^*\frac{M_{\mathrm{FS}}}{\rho^*}$$

where $\dot{M}_{\mathrm{in}}$ and $\dot{M}_{\mathrm{out}}$ are the inflow and outflow mass flow rates, M_{FS} and ρ^* are the mass and the density in the reactor, Y_k^o is the mass fraction in the inflow from the “surroundings” and Y_k^* is the mass fraction within the reactor and also (since the reactor is well mixed) that of the outflow. R_k^* is the volumetric reaction rate within the reactor.

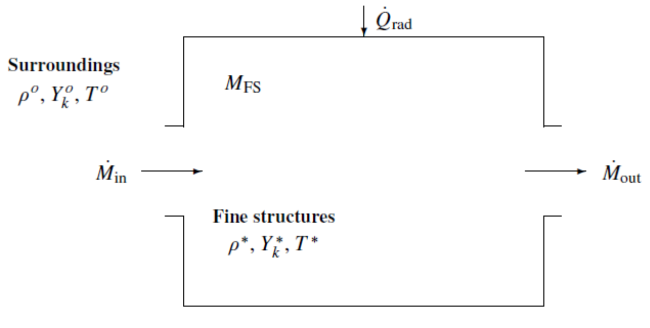


Figure 11.3: Schematical fine-structure reactor

Sketch from textbook (Ertesvåg).

With $\dot{M}_{\mathrm{in}}=\dot{M}_{\mathrm{out}}$ and the notation $\dot{m}^*=\dot{M}_{\mathrm{in}}/M_{\mathrm{FS}}$, the mass balance can be reorganized to the given expression, $R_k^*=-\rho^*\dot{m}^*(Y_k^o-Y_k^*)$.

The fine structure mass is assumed as a certain fraction, γ^*, of the total mass. Furthermore, a certain fraction, χ, of the fine structures are reacting. Thus, the reactor has a mass fraction $\gamma^*\chi$ of the total, while the remaining mass has no reactions. Averaged over all mass, the reaction rate becomes

$$\overline{R}_k = \gamma^*\chi R_k^* = -\rho^*\dot{m}^*\gamma^*\chi(Y_k^o - Y_k^*)$$

Furthermore, expressing the (mass-weighted) mean mass fraction as a mean of the reactor mass fraction Y_k^* for $\gamma^*\chi$ of the total and the surroundings mass fraction Y_k^o for the remaining $(1-\gamma^*\chi)$, gives $\tilde{Y}_k = \gamma^*\chi\cdot Y_k^* + (1-\gamma^*\chi)\cdot Y_k^o$. Reorganizing this to $(Y_k^o - Y_k^*) = \frac{1}{1-\gamma^*\chi}(\tilde{Y}_k - Y_k^*)$, leads to the 2nd expression given in the problem.

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.

See the textbook (Ertesvåg), Sect. 11.6.

A single-step global reaction can be written as $1\text{ kg fu} + \text{r kg ox} \rightarrow (1\text{+r})\text{ kg prod}$

The species (k) are “fu”, “ox” and “prod”, and the reaction rates are related as $R_{\text{fu}} = \frac{1}{r}R_{\text{ox}} = \frac{-1}{1+r}R_{\text{prod}}$

From Problem 4: $\overline{R}_k = -\frac{\rho^*\dot{m}^*\gamma^*\chi}{1-\gamma^*\chi}(\tilde{Y}_k - Y_k^*)$

The main idea is that when the single-step reaction is infinitely fast, one of the reactants (“fu” or “ox”) are fully and immediately consumed. When the least available reactant is consumed, no more of the other reactant can react. The reaction rate is then determined by the least available reactant and by the mixing (represented by $\dot{m}^*$ and γ^*).

For a fuel-lean mixture $\tilde{Y}_{\text{fu}} < \frac{1}{r}\tilde{Y}_{\text{ox}}$, all the fuel is consumed, $Y_{\text{fu}}^* = 0$, and the consumed oxidizer is that consumed in the reaction with fuel. In this case, fuel is the limiting reactant.

$\overline{R}_{\text{fu}} = [...](\tilde{Y}_{\text{fu}} - Y_{\text{fu}}^*) = [...]\tilde{Y}_{\text{fu}}$ and $\overline{R}_{ox} = r\overline{R}_{\text{fu}}$

($[...]$ is short for the quantities before the parenthesis in the expression given in Problem 4.)

For a fuel-rich mixture $\frac{1}{r}\tilde{Y}_{\text{ox}} < \tilde{Y}_{\text{fu}}$, all the oxidizer is consumed, $Y_{\text{ox}}^* = 0$, and the consumed fuel is that consumed in the reaction with oxidizer. In this case, oxidizer is the limiting reactant.

$\overline{R}_{ox} = [...](\tilde{Y}_{\text{ox}} - Y_{\text{ox}}^*) = [...]\tilde{Y}_{ox}$ and $\overline{R}_{\text{fu}} = \frac{1}{r}\overline{R}_{ox} = [...]\frac{1}{r}\tilde{Y}_{ox}$

In both cases, $\overline{R}_{\text{fu}}$ is proportional to the least of $\tilde{Y}_{\text{fu}}$ and $\frac{1}{r}\tilde{Y}_{\text{ox}}$;

thus $\overline{R}_{\text{fu}} = \frac{1}{r}\overline{R}_{ox} = [...]\tilde{Y}_{\min}$ where $\tilde{Y}_{\min} = \min(\tilde{Y}_{\text{fu}}, \frac{1}{r}\tilde{Y}_{ox})$

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.

Collision theory: When two chemicals react, their molecules have to collide with each other (in a particular orientation) with sufficient energy for the reaction to take place

Concentration: When the concentrations increase, the likelihood of them colliding increases

Temperature: Higher temperatures -> reactant molecules have more kinetic energy -> they move faster and collide more often with more energy

Pressure: Increase the number of collisions as more molecules are in the same volume.

Catalyst: Only speed up the reaction by providing an alternative route for the reaction with a lower activation energy.

The probability that a collision leads to a reaction can be expressed as a product of two factors: an energy factor, $\exp(-E_A/(R_u T))$, which expresses the fraction of collisions that occur with an energy above the threshold level necessary for the reaction, E_A, or activation energy; and a geometrical or steric factor, *p*, that takes into account the geometry of collisions between two molecules.

Arrhenius formulation: $k(T) = A \cdot T^b \exp\left(-\frac{E_A}{R_u T}\right)$ (Can incorporate T^b into *A*).

E_A is the activation energy, so the collision needs to have enough energy to get a reaction. R_u is the universal gas constant. *A* is a constant termed the pre-exponential factor or the frequency factor. Related to the collision theory, it expresses the collision frequency and the orientation, such as the steric factor.

7)

The following two-step mechanism is proposed for the conversion of ozone (O3) to oxygen (O2):

1) $O_3 \overset{k_{f,1}}{\underset{k_{r,1}}{\Leftrightarrow}} O_2 + O$, 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 O3 (d[O3]/dt) from this mechanism.

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

The rate of the reactions is expressed by the reaction rate coefficient multiplied by the concentrations of the reactants entering the reaction. For elementary reactions, the order of the reaction is the number of reacting molecules. (This may not be the case for global reactions.)

Step 1: Forward reaction: $O_3 \xrightarrow{k_{1,f}} O_2 + O$; rate: $k_{1,f}[O_3]$; order: 1

Reverse reaction: $O_3 \leftarrow O_2 + O$; rate: $k_{1,r}[O_2][O]$; order: 2

Step 2: $O + O_3 \overset{k_2}{\rightarrow} O_2 + O$; rate: $k_2[O][O_3]$; order: 2

The change in the concentration (production rate) of ozone O_3 is expressed by all the reactions producing O_3 minus all reactions consuming O_3.

$$\frac{d[O_3]}{dt} = -k_{1,f}[O_3] + k_{1,r}[O_2][O] - k_2[O][O_3] \quad (*)$$

When partial equilibrium is applied for a two-way (reversible) reaction, the forward and reverse rates are set equal. For Step 1, this becomes:

$$k_{1,r}[O_2][O] = k_{1,f}[O_3] \quad (**)$$

From this, the concentration of O (the most reactive participating species) can be expressed as

$$[O] = \frac{k_{1,f}[O_3]}{k_{1,r}[O_2]} \quad (***)$$

Since O can be difficult to measure and control, this approximation can be useful. Due to (**), the two first right-hand side terms of (*) cancel, and with (***) the final expression becomes

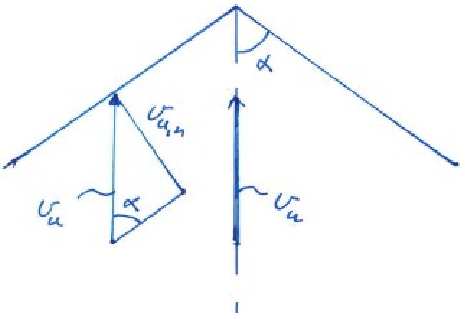
$$\frac{d[O_3]}{dt} = \frac{k_2 k_{1,f}}{k_{1,3}} \frac{[O_3]^2}{[O_2]}$$

8)

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

-- Make a sketch that illustrates how the 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?

The laminar flame speed S_L is the speed of the inflow of unburned mixture normal to the flame front. When using a Bunsen burner to measure S_L, we need to know the fuel/air mixture volumetric flow rate ($\dot{V}$) to estimate the fresh gas velocity from the nozzle, v_u $(= \dot{V}/A$, where A is the nozzle area). The steady-state flame of the burner forms a cone as sketched below. The flame front forms an angle α with the nozzle axis, and this angle can be measured. The velocity component normal to the flame front can then be determined as $S_L = v_\mathrm{u,n} = v_\mathrm{u} \sin\alpha$.



The laminar flame speed can also be expressed from the chemical time scale and the diffusivity D or viscosity ($\nu \approx D$): $S_L = (D/\tau_\mathrm{c})^{1/2}$. The chemical time scale can be expressed from the fuel reaction rate $\tau_\mathrm{c} \sim R_\mathrm{fu}^{-1}$. This expression can be used both for premixed and non-premixed flames.

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/m3 (700 g/L))

Emission index, species i from fuel C$_x$H$_y$:

$$\mathrm{EI}_i = \frac{m_i}{m_\mathrm{F}} = \frac{n_i M_i}{n_\mathrm{F} M_\mathrm{F}} = \frac{n_i M_i}{\frac{1}{x}(n_\mathrm{CO2} + n_\mathrm{CO})\cdot M_\mathrm{F}} = \frac{X_i}{(X_\mathrm{CO2} + X_\mathrm{CO})}\cdot\frac{x M_i}{M_\mathrm{F}}$$

Here, $x = 8$;

$$\mathrm{EI}_\mathrm{NO} = \frac{X_\mathrm{NO}}{(X_\mathrm{CO2} + X_\mathrm{CO})}\cdot\frac{x M_i}{M_\mathrm{F}} = \frac{16\cdot 10^{-6}}{(0.125 + 25\cdot 10^{-6})}\frac{8\cdot 30}{114}\frac{\mathrm{kg}}{\mathrm{kg}} = 2.69\cdot 10^{-4}\frac{\mathrm{kg}}{\mathrm{kg}} = 0.269\frac{\mathrm{g}}{\mathrm{kg}}$$

Specific emissions:

$$\frac{\text{mass of NO}}{\text{length}} = \frac{m_\mathrm{NO}}{\ell} = \frac{V_\mathrm{F}\rho_\mathrm{F}}{\ell}\frac{m_\mathrm{NO}}{m_\mathrm{F}} = \frac{5.0\ \mathrm{L}}{100\ \mathrm{km}}\cdot 0.700\frac{\mathrm{kg}}{\mathrm{L}}\cdot 0.269\cdot 10^{-3}\frac{\mathrm{kg}}{\mathrm{kg}} = 9.4\cdot 10^{-6}\frac{\mathrm{kg}}{\mathrm{km}} = 9.4\frac{\mathrm{mg}}{\mathrm{km}}$$

The relation between wet mole fractions (H2O included) and dry mole fractions (H2O excluded) can be found from the global reaction balance (here, $\lambda = 1$) :

$$\mathrm{C_8H_{18}} + \lambda\cdot 12.5(\mathrm{O_2} + 3.76\mathrm{N_2}) \rightarrow 8\mathrm{CO_2} + 9\mathrm{H_2O} + (\lambda\text{-}1)\cdot 12.5\ \mathrm{O_2} + \lambda\cdot\underbrace{12.5\cdot 3.76}_{47.0}\mathrm{N_2}$$

Product (mol per mol fuel): $n_\mathrm{wet} = 8 + 9 + 0 + 47.0 = 64.0$; $n_\mathrm{dry} = 8 + 0 + 47.0 = 55.0$

$$X_{i,\mathrm{wet}} = n_i / n_\mathrm{wet}\ ;\ X_{i,\mathrm{dry}} = n_i / n_\mathrm{dry}\ ;\ n_i = X_{i,\mathrm{dry}} n_\mathrm{dry} = X_{i,\mathrm{wet}} n_\mathrm{wet}\ ;\ X_{i,\mathrm{dry}} = X_{i,\mathrm{wet}}\frac{n_\mathrm{wet}}{n_\mathrm{dry}}$$

$$X_\mathrm{NO,dry} = X_\mathrm{NO,wet}\frac{n_\mathrm{wet}}{n_\mathrm{dry}} = 16\cdot 10^{-6}\frac{64.0}{55.0} = 18.6\cdot 10^{-6} = 18.6\ \mathrm{ppm}$$

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).

For diesel engines, operation strategies that lower the combustion temperature are common for reducing NOx emissions. Some examples of these strategies are LTC and EGR, which provide favorable conditions by diluting and premixing fuel and oxidizer. For more strategies the reader is referred to Chapter 15 in Turns book: An introduction to combustion

Low-Temperature Combustion (LTC) Strategies:
Low-temperature combustion (LTC) strategies aim to minimize NOx formation by reducing peak combustion temperatures and mixing. Examples of strategies include techniques such as homogeneous charge compression ignition (HCCI), premixed charge compression ignition (PCCI), and stratified charge compression ignition (SCCI).

HCCI relies on autoignition of a homogeneous air-fuel mixture at low temperatures and high pressures, resulting in a more gradual combustion process and lower peak temperatures than conventional diesel combustion.

PCCI combines elements of both conventional diesel combustion and gasoline-like homogeneous charge combustion, using an early injection of fuel to create a premixed charge that ignites by compression at lower temperatures.

SCCI involves injecting fuel in multiple stages to create a stratified mixture with varying fuel-air ratios, allowing for more precise control over combustion timing and temperature.

Exhaust Gas Recirculation (EGR):
EGR systems recirculate some of the engine's exhaust gases into the combustion chamber. This reduces the oxygen concentration in the combustion chamber, lowering the combustion temperature.

Lower combustion temperatures lead to reduced nitrogen oxides (NOx) formation during combustion, as NOx formation is highly dependent on temperature.

EGR systems can be cooled or uncooled, depending on whether the recirculated exhaust gases are passed through a cooler before being reintroduced into the engine.

If NOx is produced, then after treatment systems such as Selective Catalytic Reduction (SCR) or Selective non-catalytic reduction (SNCR) can be used. Both of these utilize the thermal De-NOx mechanism. For SNCR, the temperature is important to control since it depends on the thermal De-NOx mechanism without a catalytic converter, which can be more expensive.

Selective Catalytic Reduction (SCR):
SCR systems reduce NOx emissions by converting nitrogen oxides (NOx) into harmless nitrogen (N_2) and water (H_2O) through a chemical reaction. This reaction occurs in the presence of a catalyst, typically made of materials like titanium oxide or vanadium oxide.

In the SCR process, a reducing agent, such as urea-based AdBlue, is injected into the exhaust stream before it reaches the SCR catalyst. The reducing agent reacts with the NOx over the catalyst surface, breaking it into nitrogen and water.

This highly efficient process can achieve NOx reduction rates of up to 90%.

Lean NOx Trap (LNT):
LNT systems utilize a special catalyst to trap and store NOx during lean-burn conditions (excess oxygen in the exhaust). Periodically, the engine management system adjusts the air-fuel mixture to rich conditions, releasing and converting the stored NOx into harmless gases.