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Advanced Process Control

Modelling and Control of Energy Systems

(Prof. Casella)

Written Exam – July 22nd, 2021

Question 1

Consider a pipe carrying a fluid that can be described as a perfect gas.

Discuss the time scales of dynamic phenomena related to mass, momentum, and energy conservation, pointing out what are the basic assumptions and equations behind each result.

Question 2

A certain thermal power plant is structured in two sub-units, that are connected by a pipe carrying a hot liquid from one sub-unit to the other. The geometrical and operating data are reported below. This plant needs to be described by a numerical dynamic simulation model, that will be used to analyze control-relevant dynamic behaviour and to help the control design activity. The feedback loops in the plant are expected to have a maximum bandwidth around 0.1 rad/s.

Discuss the impact that such a pipe could have on the static and dynamic behaviour of the overall plant, in terms of mass, momentum, and energy, in particular which phenomena may be relevant and which ones could be neglected. You may use the results of the analysis carried out for 1D heat exchangers to help you in this task.

Based on the results of this discussion, write down a suitaby simplified, lumped-paramer, first-order 0D model that captures the dominant dynamic phenomenon of that pipe, and could be used to model that pipe in the overall numerical model of the plant with a small overhead in terms of computational complexity. Discuss the validity limits of such a model.

Fluid density $\rho = 900$ kg/m^3
Fluid specific heat capacity $c_p = 3200$ J/kg.K
Pipe internal diameter $D = 20$ cm
Pipe thickness $s = 3$ mm
Pipe material density $\rho_m = 8700$ kg/m^3
Pipe material specific heat capacity $c_w = 560$ J/kg.K
External heat transfer coefficient $\gamma_e = 4$ W/m^2.K
Internal heat transfer coefficient $\gamma_i = 1200$ W/m^2.K
Length of the pipe $L = 30$ m
Fanning friction factor $c_f = 0.005$
Design mass flow rate $w = 80$ kg/s

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Question 3 (Only for the Advanced Process Control exam, not for Modelling and Control of Energy Systems)

With reference to the problem of controlling the turbine inlet temperature in a Rankine cycle by means of de-superheating

- describe the structure of the process
- present and briefely discuss a dynamic model that captures the control-relevant dynamic behaviour, highlighting what are the modelling assumptions and the considered phenomen
- discuss the control strategy for such process, including criteria for controller tuning

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ex.1:

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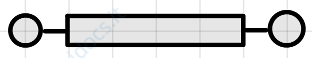
Oss. 3:



- MASS + MOMENTUM (WAVE PROPAGATION):

$$c = \frac{1}{\sqrt{\frac{\rho}{P_E}+\frac{\rho}{P_E}}} \cong \sqrt{\frac{P_E}{\rho}} = 1527 \ m/s$$

$$\tau = \frac{L}{c} = \frac{30}{1527} = 0{,}015 \ s = 15 \ ms \quad \rightarrow \omega = \frac{1}{\tau} = 66{,}67 \ rad/s$$

because $\omega_c = 0{,}1 \ rad/s$, the dynamics of wave propagation is so fast that can be neglected

- ENERGY BALANCE (HEAT EXCHANGER):

$$\Delta T_o = e^{-\alpha_o} e^{-(\tau+\tau')} \Delta T_i \qquad (\text{for liquids, we assume } \gamma_i \to \infty) \qquad \alpha_i = \frac{\gamma_i D \pi L}{wc} \cong 0{,}03$$

$$\tau + \tau' = \frac{mc + m_w c_w}{wc} \cong \frac{mc}{wc} = \frac{m}{w} = \frac{\rho A}{w} = \frac{\rho \frac{D^2}{4}\pi}{w} = 10{,}6 \ s = \tau \quad \rightarrow \omega \cong 0{,}1 \ rad/s$$

The dynamics of 1D energy is not negligible since $\omega \cong \omega_c$.

The STATIC BEHAVIOUR is:

$$\Delta T_o = e^{-\alpha_o} \Delta T_i \quad \rightarrow \alpha_o = \frac{\gamma_{TOT}}{wc} = \frac{\frac{\gamma_{iw}\gamma_{we}}{\gamma_{iw}+\gamma_{we}}}{wc} \overset{\gamma_{iw} \gg \gamma_{we}}{\cong} \frac{\gamma_{we}}{wc} = \frac{\gamma_e \overset{\cong \omega_i = D}{\omega_e} L}{wc} = \frac{\overset{=15{,}36}{\gamma_e D L}}{wc} = 2{,}9 \cdot 10^{-4}$$

$$\Rightarrow \mu_o = e^{-\alpha_o} \cong 1 \quad \rightarrow \text{we don't want to exchange heat } (\gamma_i \gg \gamma_e)$$

The dominant dynamics of the pipe refers to the energy exchange, so we can find a 0D model from energy balance:

$$\frac{d}{dt} \underset{m}{\rho A} \underset{cT}{e} = w(h_i - h_o) + Q + \cancel{W} + \cancel{F_v}$$

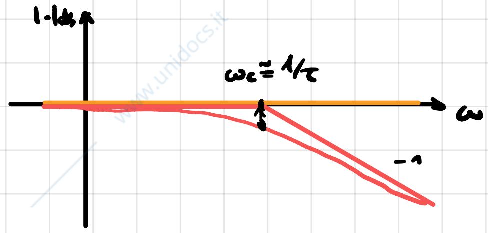
$$\begin{cases} mc\frac{dT}{dt} = wc(T_i - T_o) + Q \\ m_w c_w \frac{dT_w}{dt} = -Q + \cancel{Q_{ext}} \end{cases} \quad \overset{T \cong T_w}{\Rightarrow} \quad (mc + m_w c_w)\frac{dT_o}{dt} = wc(T_i - T_o)$$

$$(mc + m_w c_w)\frac{d\Delta T_o}{dt} = c(\bar{T}_i - \bar{T}_o)\Delta w + \bar{w}c(\Delta T_i - \Delta T_o) \quad \Big\downarrow \mathcal{L}$$

$$(mc + m_w c_w) s \Delta T_o = c(\bar{T}_i - \bar{T}_o)\Delta w + \bar{w}c\Delta T_i - \bar{w}c\Delta T_o$$

$$\Rightarrow \Delta T_o = \frac{c(\bar{T}_i - \bar{T}_o)}{\bar{w}c + (mc + m_w c_w)s}\Delta w + \frac{\bar{w}c}{\bar{w}c + (mc + m_w c_w)s}\Delta T_i$$

$$\Rightarrow \Delta T_o = \frac{\bar{w}c}{\bar{w}c + (mc + m_w c_w)s}\Delta T_i = \frac{1}{1 + \underbrace{\frac{mc + m_w c_w}{\bar{w}c}}_{\tau + \tau'} s} \cong \frac{1}{1 + s\tau}$$



$$\left| \frac{1}{1 + j\omega_c \tau} \right| = \frac{1}{\sqrt{1 + \omega_c^2 \tau^2}} = \frac{1}{\sqrt{1 + \omega_c^4}} \cong 1$$

$$\measuredangle \frac{1}{1 + j\omega_c \tau} = -\arctan(\underset{\sim 1/\omega_c}{\omega_c \tau}) \cong -\arctan(1) = -45^\circ$$

$$\measuredangle = -\frac{\omega_c \tau}{c}\frac{\pi}{180} = -57^\circ \quad \Big\} \text{VALID}$$

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Because the dynamics of the approx. model is near we in the neighbourhood of the validity limitation, would be better to use a 10 norm (for phase, the gain is ~ the same).

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es. 3:

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