Simulation of alternative temperature control structures of a biogas reactor in a wastewater treatment plant

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Abstract: This study deals with the simulated different temperature control strategies on an anaerobic digestion reactor in a wastewater plant. This simulation is based on a mathematical model that is the outcome of a dynamic energy balance on the reactor. The PI controller tuning method is the Skogestad method. From the simulation, a preferred control structure has been identified.

Keywords: Wastewater treatment, energy balance, thermophile, anaerobic digestion, temperature control, Skogestad PI controller tuning method, simulation.

INTRODUCTION

The temperature of Anaerobic Digestion (AD) has significant effects on methane production as well as on sludge hygienisation. The temperature stability has been found by several studies to be one of the most important parameters (Leitao, Haandel, Zeeman, & Lettinga, 2006), (Chae, Jang, Yim, & Kim, 2008). Since the methane forming bacteria is sensitive to temperature changes, accurate temperature control is essential. The consensus is that temperature changes greater than 1℃/d affect process performance, thus temperature variations of less than 1℃/d are recommended (Metcalf & Eddy, 2003)

In this study, alternative temperature control structures of an AD biogas reactor in a wastewater treatment plant (WWTP) are compared in simulations which are based on energy balance, implemented in LabVIEW. The WWTP is the VEAS plant which is the largest WWTP in Norway, for about 700,000 population equivalent (pe), treating 100-120 million m^3/y of raw unsegregated wastewater, or in average 3.5 m^3/s. Energy produced by altogether four 6000 m^3 AD reactors in the form of methane gas amounts to about 70 GWh used for electricity and heat production.

The main load changes or disturbances are variations in the reactor flow rate and temperature of the reactor inflow during the reactor operation cycle, and heat loss as convection. The comparison is based on different criteria, cf. Table 1.

MATERIALS AND METHODS

Process description

In the VEAS plant, the reactors are operated at thermophile conditions to achieve a hygienised sludge by heating up to 55℃ with a residence time of 2 hours to kill harmful organisms. Reactor operation includes this hygienisation stage to ensure sludge properties as required by the Regulation of European Parliament EN 1774/2002(EC, 2002) (Klemes, Smith, & Kim, 2008). To this end, the reactors are operated in a sequence of phases as described in the following, see also Fig. 1.

- Filling Phase (45 min): Pumping raw sludge to reactor from raw-sludge storage tank, and also pumping digested sludge through heat exchangers. Note: In the current reactor operation regime, heat can be added to the reactor only in the filling phase.
- Holding Phase (120 min): Circulating digested sludge and no new feed flow for sludge hygeinisation purposes. Reactor sludge is retained at minimum 55 °C for minimum of 2h.
- Emptying phase (15 min): Transferring the hygienised digested sludge to a buffer tank.

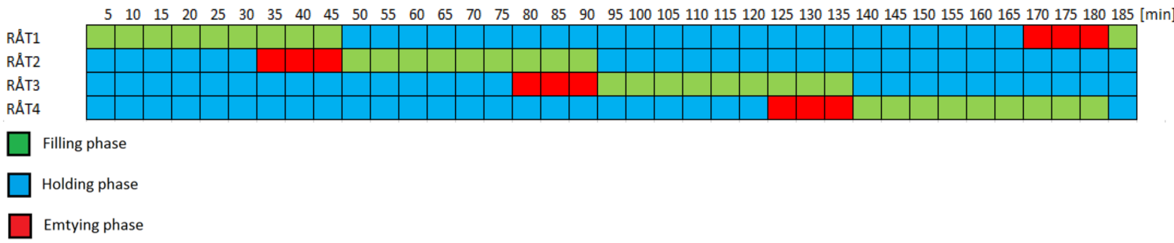


Figure 1. The three various phases of one cycle of operation of AD reactor

Mathematical model

The mathematical model which is the basis of the simulator, which is implemented in LabVIEW, see Figure 2, is a dynamic energy balance of the reactor contents assuming thermal properties as of water:

$$\dot{T} = \frac{1}{\rho c V(t)}\left[\rho c F_{in} T_{in} - \rho c F_{in} T - H(T - T_{env})\right] \quad (1)$$

The model parameter descriptions and values are given in Table 1.

Table 1. Values of model parameters of reactor temperature in alphabetical order

Parameter	Value	Unit
c	4186	[J/(kg°K)]
F_{in}	Eq. (3)	[m^3/s]
H	7006	[W/°K]
ρ	1000	[kg/m^3]
T_{env}	20	[°K]
T_{in}	Eq.(4)	[°K]
V	5700	[m^3]

H is a heat transfer coefficient that depends on the geometric parameters of the reactor tank.

$$H = \frac{KA}{d} \quad (2)$$

where K is thermal conductivity of the reactor [J/(sm°K)], d is the thickness of the wall of the reactor [m] and A is the area of the lateral wall of the reactor tank [m^2].

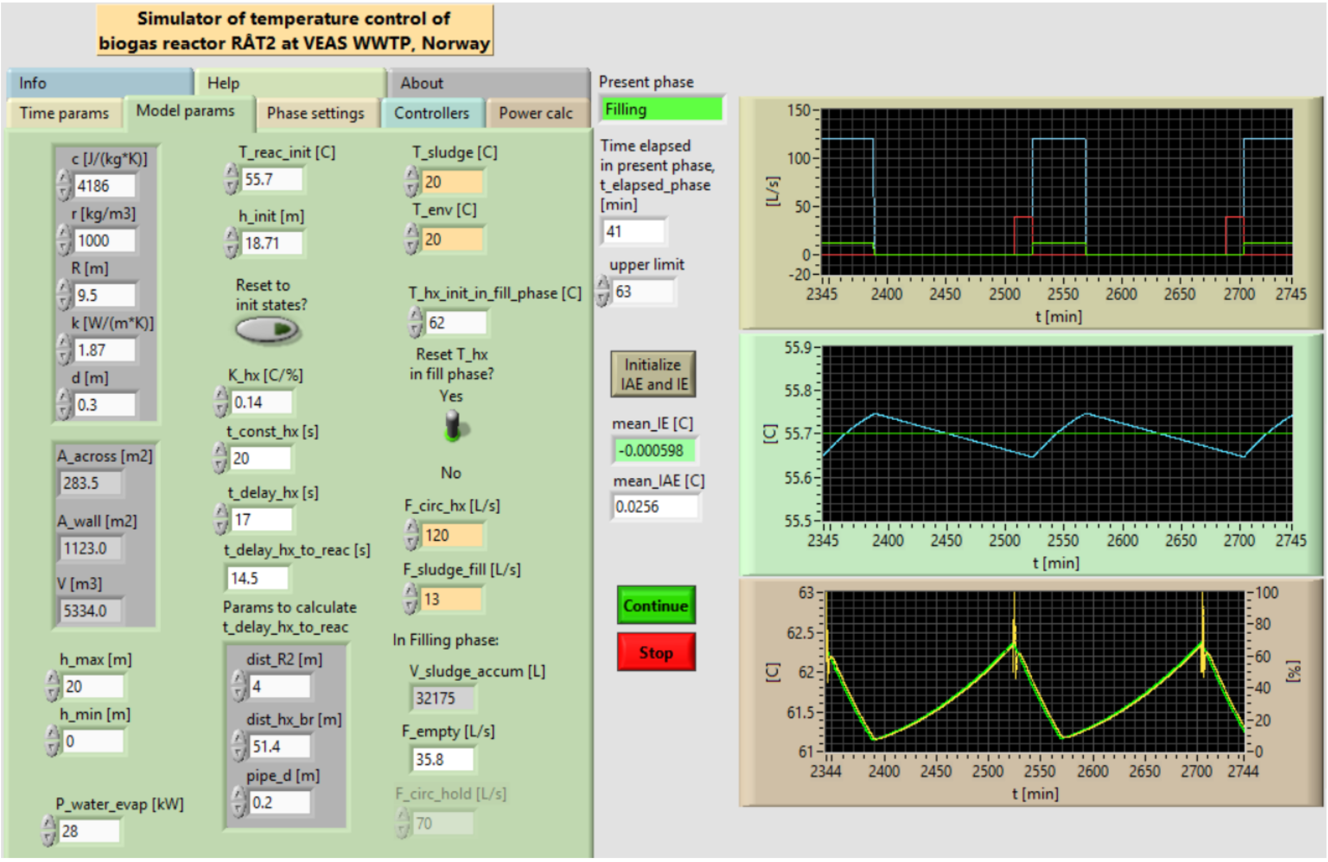
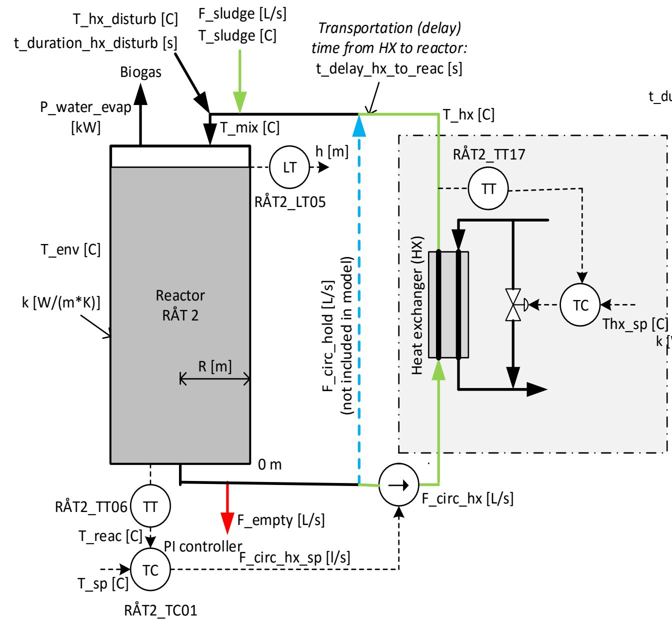


Figure 2. Example front panel of LabVIEW simulator (for one of the control structures studied)

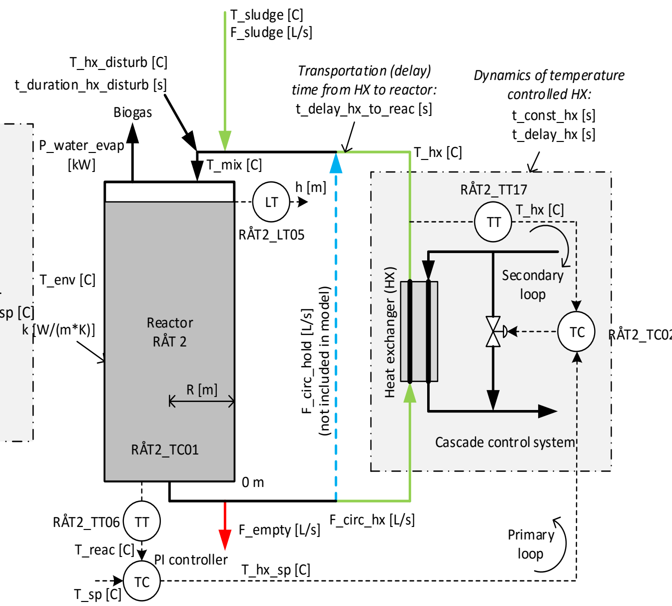
Control strategies

Alternative reactor temperature control structures studied:

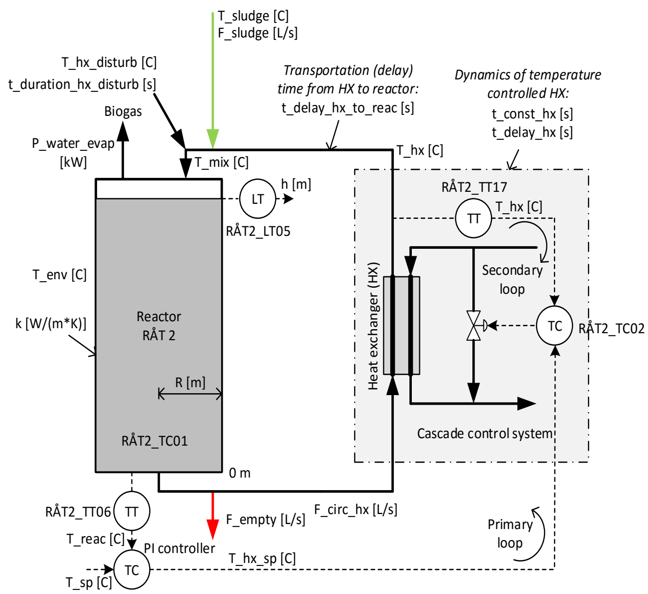
- *Structure 1*: Single loop (feedback) control using recirculation flow rate as control variable, see Figure 3a. (With the controller in manual mode, this structure mimics the present strategy at VEAS.) The temperature of the heat exchanger, T_{hx}, is assumed constant 62 °C.
- *Structure 2*: Cascade control with reactor temperature controller as primary controller and heat exchanger temperature controller as secondary controller, see Figure 3b. The purpose of this strategy is to make the temperature of the heat exchanger, T_{hx}, as close to the reactor temperature, T_{reac}, as possible to avoid disturbing the microorganisms unnecessarily. The recirculation flow through the heat exhanger, $F_{circ,hx}$, is fixed and set as high as possible. It is expected that this will make T_{hx} as close to T_{reac} as possible.
- *Structure 3*: Cascade control, similar to Structure 2, but assuming heat circulation flow during the holding phase also, see Figure 3c. This structure requires an independent heat exchanger for each specific reactor. (Comment: In the present structure, three heat exchangers are sequentially shared among the four reactors, making using them for heating also in the holding phase, impossible.)
- *Structure 4*: Cascade control, similar to Structure 2, but heating the raw sludge (reactor feed) with a temperature controlled heat exchanger to a temperature close to the reactor temperature setpoint, see Figure 3d. The purpose of this structure is to reduce the need for heating the digested sludge, thereby reducing the stressing of the microorganisms.



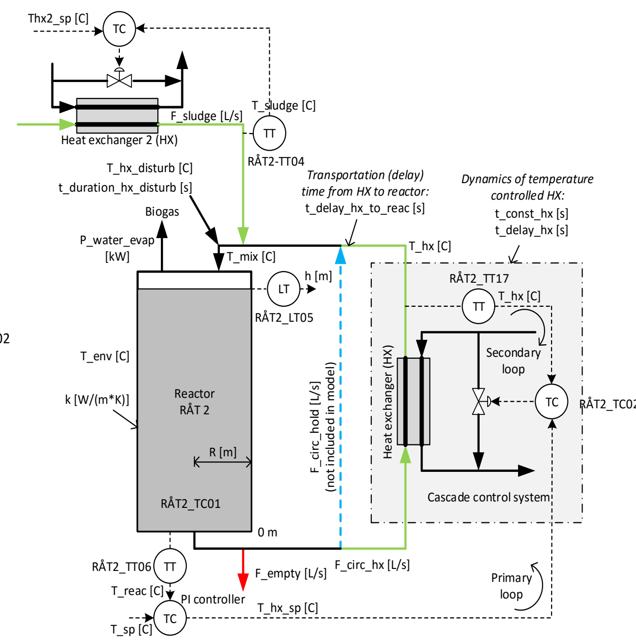
a) Structure 1.



b) Structure 2.



c) Structure 3.



d) Structure 4.

Figure 3. Piping and Instrumentation diagrams (P&IDs) of alternative temperature control structures (Figures a, b, c, d) in the three operational phases shown in Figure 1. The colour of a pipe in the P&IDs indicates when the pipe is "open" in the various phases.

Experiments

The most challenging operating conditions are assumed: Coldest raw sludge temperature, namely 20°C, with largest sludge flow, 13 l/s. Where a heat exchanger is used for temperature control of the raw sludge, the sludge temperature is assumed 55.7 °C (setpoint of reactor temperature).

RESULTS

Table 2 summarizes the results of the simulations for the different control structures in the most challenging condition.

Table 2. Results of the four different control structures (Sn). The numbers in the table apply to steady state. mIAE is mean of integral of absolue value of control error. The results is for the assumed most challenging condition of operation.

	mIAE	**Max reac. temp. [°C]**	**Max reac. temp. change [°C]**	**Heat exchanger temperature [°C]**			**Cirulation flow [l/s]**			**Control parameters**	
				Min	**Max**	**Mean**	**Min**	**Max**	**Mean**	**K_c**	**T_i [min]**
S1	0.0105	55.72	0.053	62.00	62.00	62.00	82	105	92	503 [(l/s)/°C]	60.0
S2	0.0257	55.75	0.11	61.15	63.05	62.92	120	120	120	13 [°C/°C]	122
S3	0.003	55.72	0.030	55.73	62.31	57.47	120	120	120	250 [°C/°C]	5.72
S4	0.0256	55.75	0.10	57.28	58.49	57.89	120	120	120	13 [°C/°C]	122

Structure 3 with control of reactor temperature during both the filling and holding phases is preferred as it has the smallest value both of mIAE (mean IAE) and of maximum temperature change. But it needs a separate heat exchangers for each reactor.

Comparing Structures 1 and 2 indicates that using the recirculation flow as control variable is comparable with using heat exhanger temperature as control variable during the filling phases. To compare Structure 1 and 2 , it is required to check the criterias in the normal condition. Based on monitoring on the sludge flow and its temperaure for 5 days in the VEAS plant, it is considred the average of these parameteres as a normal opperating condition which are respectively 9.15 l/s and 24.13 °C. Since the circulated flow is apart of degisted sludge which passess from heat exchangers, it is better the temperature of circulated flow should be close to reactor temperature as far as possible. Therefore the preferred control structure is Structure 2 based on the results of the simulation for both control structures in the normal condition that are shown in Table 3.

Table 3. Results of the two different control structures (Sn) in the normal operating condition.

	mIAE	**Max reac. temp. [°C]**	**Max reac. temp. change [°C]**	**Heat exchanger temperature [°C]**			**Cirulation flow [l/s]**		
				Min	**Max**	**Mean**	**Min**	**Max**	**Mean**
S1	0.0105	55.72	0.053	62.00	62.00	62.00	56	77	60
S2	0.0254	55.75	0.102	59.71	60.90	60.05	120	120	120

THE SUGGESTED CONTROL STRUCTURE FOR VEAS

According to the results of the simulation, Structure 3 with control of reactor temperature during both the filling and holding phases has the best result with smallest values for mIAE and maximun temperature change. However, it is not possible to implement Structure 3 in the VEAS plant with the present plant equipment since three other reactors use the heat exchanger while one reactor is being in the holding phase. Therefore, Structure 2 is the preferred control structure that can implement in VEAS with smallest temperature changes on the reactor and recirculation digested sludge.

Controller tuning

Control objective and control variable

The reactor temperature is the process output variable to be controlled with T_{hx} as a control variable. Figure 4 shows a block diagram of the reactor temperature control system.

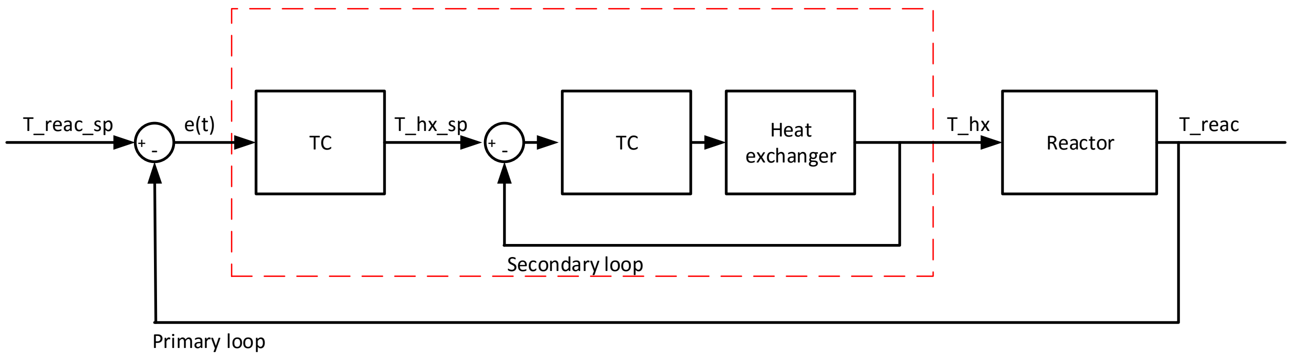


Figure 4. The block diagram of structure 2

Controller functions

The controllers in both primary and the secondary loop are Proportional-Integral (PI) controllers and they must be tuned regarding to the thermal dynamics of process to be controlled. The PI controller function is shown in Equation (3):

$$u(t) = K_c\, e(t) + \frac{K_c}{\tau_i}\int_0^t e(\tau)d\tau \tag{3}$$

where $e(t)$ is the control error, i.e. temperature setpoint minus temperature measurement. K_c and τ_i must be determined by a proper controller tuning method.

Note: The secondary controller is already tuned for fast and stable control, and details about the tuning of this controller is not described in this paper. It is assumed that T_{hx} follows T_hx_sp relatively accurately, due to the fast secondary loop.

Primary controller tuning

The primary reactor temperature controller is tuned by the Skogestsd method assuming “integrator” with time-delay process dynamics (Skogestad, 2003) as described in the following.

The infeed flow is the sum of the sludge flow and circulation flow:

$$F_{in} = F_{sludge} + F_{circ} \tag{4}$$

The infeed temperature is a function of the temperatures both sludge and circulation flows:

$$T_{in} = \frac{F_{sludge}\, T_{sludge} + F_{circ}\, T_{hx}}{F_{sludge} + F_{circ}} \tag{5}$$

By using Eqs. (4) and (5) in Eq. (1), the process model can be written as

$$\dot{T}(t) = \frac{F_{circ}}{V(t)} . T_{hx}(t - T_{delay}) + X\ (t) \tag{6}$$

where

$$X(t) = \frac{1}{\rho c V(t)} \left[\rho c F_{sludge} T_{sludge} - \rho c (F_{sludge} + F_{circ}) T(t) - H(T(t) - T_{env})\right] \tag{7}$$

T_{delay} is estimated based on distance between the heat exchanger and the reactor tank regarding to the circulation flowrate and the size of the transfer pipe. In this plant, $T_{delay} = 51.1s$.

A conservative controller tuning result is obtained by disregarding the energy loss terms, i.e. the last two additive terms, in Eq. 7. Furthermore, the first additive term in Eq. 6 is independent of T_{hx}. Thus, the following process model is used as a basis for Skogestad tuning:

$$\dot{T}(t) = \frac{F_{circ}}{V(t)} * T_{hx}(t - T_{delay}) = Ki * T_{hx}(t - T_{delay}) \tag{8}$$

which is an integrator (from T_{hx} to T), with

$$K_i = \frac{F_{circ}}{V(t)} \tag{9}$$

According to the Skogestad method , the PI controller-setting for this integrator process is :

$$K_c = \frac{1}{K_i\ (T_{delay} + T_c)} \tag{10}$$

and

$$\tau_i = 2(T_{delay} + T_c) \tag{11}$$

T_c is the time-constant of the control system. It is adjusted during the simulation to achieve a proper response, in this case T_c is specified 60 min. In Structure 2, the maximum circulation flow rate is considered and in this plant it is 120 l/s. The volume V of material in the tank is approximately 5700 m^3. Thus, K_c and T_i become 13 °C/°C and 7302 s, respectively.

DISCUSSION AND CONCLUSION

Structure 3 with control of reactor temperature during both the filling and holding phases is preferred as it has the smallest value both of mIAE (mean IAE) and of maximum temperature change during the phases of operation (i.e., filling, emptying, holding phases). This control structure can only be applied on the plants which have a separate set of heat exchangers for each biogas reactor.

It is interesting to compare Structure 2 and 4: comparing two structures shows that a heat exchanger on the raw sludge is beneficial as it reduces the need for temperature change in recirculation. Comparing Structures 1 and 2 indicates that using the recirculation flow as control variable is comparable with using heat exhanger temperature as control variable. With the former, possible drawbacks in cases of relatively larger recirculation flow are: Heat exchanger dynamics, as gain, time-constant and time-delay, will vary with flow, reactor homogeneity may vary on the flow, and transport delay from heat exchanger to reactor will vary.

FUTURE WORK

Based the results of this simulation project, it has been decided to actually implement Structure 2 on the biogas reactors in the VEAS plant. Results of the practical implementation will be reported and discussed in a future publication.

NOMENCLATURE OF MODEL OF REACTOR TEMPERATURE

The nomenclature is in alphabetical order.
A [m^2]: Area of the lateral wall of the reactor tank.
c [J/(kg°K)]: Specific heat capacity of the sludge.
d [m]: Thickness of the wall of the reactor.
F_{circ} [m^3/s] or [l/s]: Circulated digested sludge flow.
F_{in} [m^3/s]: Infeed flow consists of the raw sludge and circulated digested sludge.
F_{sludge} [m^3/s] or [l/s]: Raw sludge flow.
H [W/°K]: Heat transfer coefficient.
K [J/(sm°K)]: Thermal conductivity of the reactor.
ρ[kg/m^3]: Density of the sludge.
T_{env}[°K]: Temperature of environment around reactor.
T_{hx} [°K]: Temperature of the circulated digested sludge flow.
T_{in} [°K]: Temperature of the infeed flow.
T_{sludge}[°K]: Temperature of the raw sludge flow.
V[m^3]: Volume of sludge in the reactor.

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