CASCADE FUZZY CONTROL OF A TUBULAR CHEMICAL REACTOR

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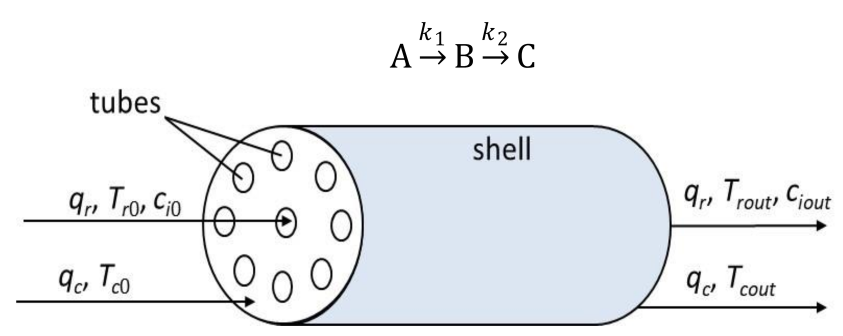
Aims

- To compare cascade control with type-1 fuzzy controllers, type-2 fuzzy controllers and PID controllers on the case study of a tubular chemical reactor.
- To show that both types of fuzzy controllers can assure better values of followed performance indices and higher energy savings measured by the coolant consumption during control of the tubular chemical reactor.

Scheme of a tubular chemical reactor



Tubular chemical reactor with co-current cooling in the jacket

Mathematical model of the tubular reactor

Mass balance of the component A

$$\frac{\partial c_A(z,t)}{\partial t} + w_r(t)\frac{\partial c_A(z,t)}{\partial z} = -k_{1\infty} e^{-\frac{E_1}{RT_r(z,t)}} c_A(z,t)$$
$$c_A(z,0) = c_A^s(z),\ c_A(0,t) = c_{A0}(t)$$

Mass balance of the component B

$$\frac{\partial c_B(z,t)}{\partial t} + w_r(t)\frac{\partial c_B(z,t)}{\partial z} = k_{1\infty} e^{-\frac{E_1}{RT_r(z,t)}} c_A(z,t) - k_{2\infty} e^{-\frac{E_2}{RT_r(z,t)}} c_B(z,t)$$
$$c_B(z,0) = c_B^s(z),\ c_B(0,t) = c_{B0}(t)$$

Heat balance of the reaction mixture

$$\frac{\partial T_r(z,t)}{\partial t} + w_r(t)\frac{\partial T_r(z,t)}{\partial z} = \frac{(-\Delta_r H)_1 k_{1\infty} e^{-\frac{E_1}{RT_r(z,t)}} c_A(z,t) + (-\Delta_r H)_2 k_{2\infty} e^{-\frac{E_2}{RT_r(z,t)}} c_B(z,t)}{\rho_r c_{pr}} - \frac{4U_1}{d_1 \rho_r c_{pr}}\left(T_r(z,t) - T_w(z,t)\right)$$
$$T_r(z,0) = T_r^s(z)\,,\ T_r(0,t) = T_{r0}(t)$$

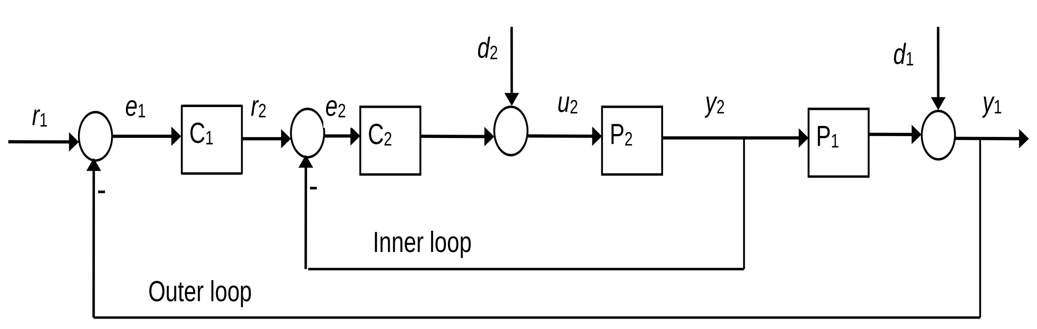
Heat balance of the inner-tube wall

$$\frac{\partial T_w(z,t)}{\partial t} = \frac{4}{(d_2^2 - d_1^2)\rho_w c_{pw}}\left[d_1 U_1\left(T_r(z,t) - T_w(z,t)\right) + d_2 U_2\left(T_c(z,t) - T_w(z,t)\right)\right]$$
$$T_w(z,0) = T_w^s(z)$$

Heat balance of the coolant

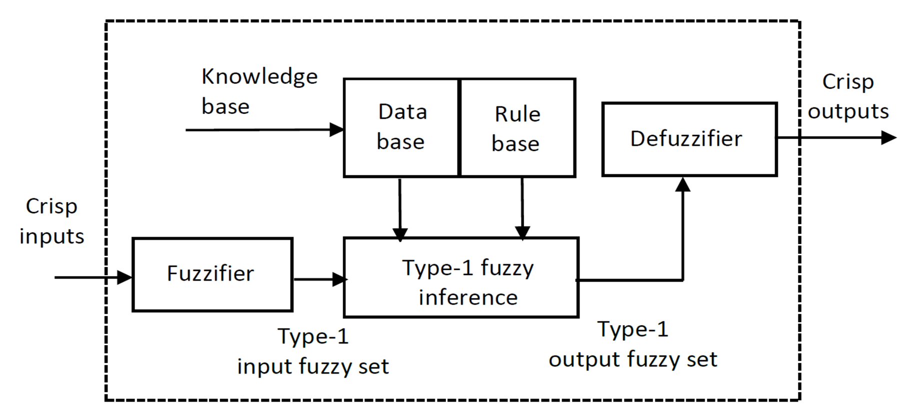
$$\frac{\partial T_c(z,t)}{\partial t} + w_c(t)\frac{\partial T_c(z,t)}{\partial z} = \frac{4 n d_2 U_2}{(d_3^2 - n d_2^2)\rho_c c_{pc}}\left(T_w(z,t) - T_c(z,t)\right)$$
$$T_c(z,0) = T_c^s(z)\,,\ T_c(0,t) = T_{c0}(t)$$

Cascade control



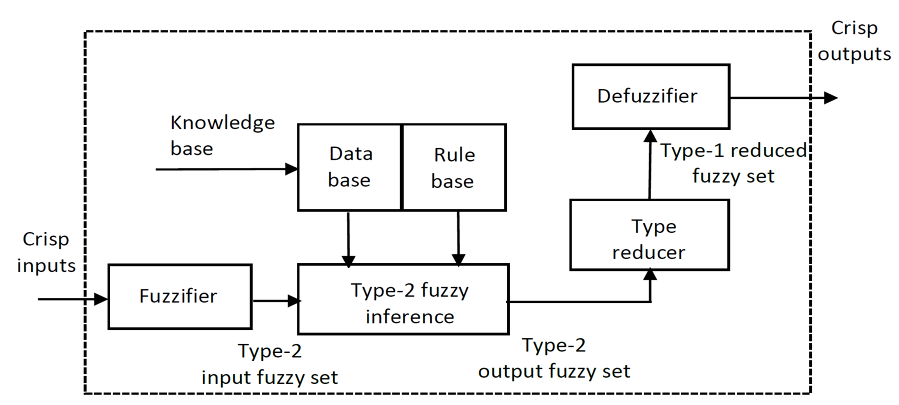
Scheme of a cascade control system

Fuzzy control – type-1 fuzzy controller



Type-1 fuzzy controller

Fuzzy control – type-2 fuzzy controller



Interval type-2 fuzzy controller

Secondary type-1 and type-2 fuzzy P controllers

Sugeno-type fuzzy inference systems with 2 rules:

$$If\ e\ is\ A_i\ Then\ f_i = p_i e + q_i$$

Gaussian membership function:

$$\mu(x) = e^{-\frac{(x-c)^2}{2\sigma^2}}$$

Parameters of Gaussian functions, antecedent and consequent parameters

Rule	σ_i	c_i	A_i	p_i	q_i
1	5.93	-14.79	A_1	- 0.029	0.23
2	5.93	-0.81	A_2	- 0.031	0.24

Primary type-1 and type-2 fuzzy PD controllers

Sugeno-type fuzzy inference systems with 6 rules:

$$If\ e\ is\ A_i\ and\ \frac{de}{dt}\ is\ B_i\ Then\ f_i = p_i e + q_i \frac{de}{dt} + r_i$$

Antecedent parameters and consequent parameters

Rule	A_i	B_i	p_i	q_i	r_i
1	A_1	B_1	121.29	-16.33	316.04
2	A_1	B_2	-22.92	-68.84	329.37
3	A_2	B_1	87.13	-192.30	201.02
4	A_2	B_2	30.52	128.56	370.74
5	A_3	B_1	103.65	-28.07	142.95
6	A_3	B_2	84.70	-4.02	178.70

Primary type-1 and type-2 fuzzy PID controllers

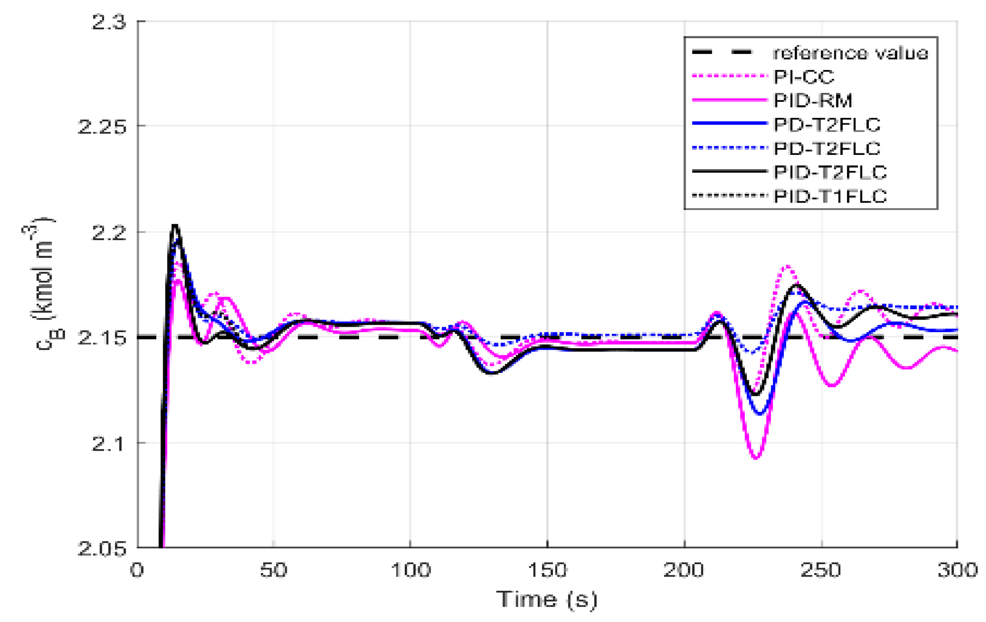
Sugeno-type fuzzy inference systems with 8 rules:

$$If\ e\ is\ A_i\ and\ \frac{de}{dt}\ is\ B_i\ and \int e\,dt\ is\ C_i\ Then\ f_i = p_i e + q_i \frac{de}{dt} + r_i \int e\,dt + s_i$$

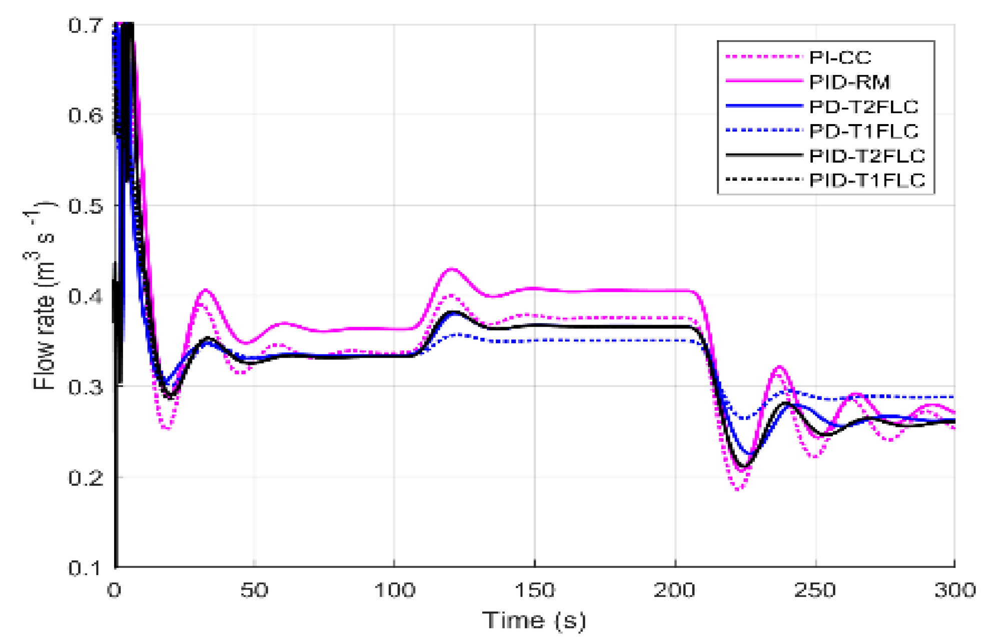
Antecedent parameters and consequent parameters

Rule	A_i	B_i	C_i	p_i	q_i	r_i	s_i
1	A_1	B_1	C_1	52.44	-0.41	132.53	45.48
2	A_1	B_1	C_2	25.95	11.54	31.96	52.56
3	A_1	B_2	C_1	27.66	-0.40	0.18	330.32
4	A_1	B_2	C_2	-2.44	0.07	0.15	330.53
5	A_2	B_1	C_1	129.66	91.08	21.09	111.06
6	A_2	B_1	C_2	141.61	-18.23	6.13	66.79
7	A_2	B_2	C_1	144.14	-2.60	11.26	85.82
8	A_2	B_2	C_2	13.47	-2.26	50.51	16.70

Simulation results



Control responses of the product concentration



Trajectories of the manipulated variable

Numerical values of performance indices: total consumption of cooling water V during control, integral absolute error IAE, and integral square error ISE

Scenario	Primary controller	Secondary controller	V (m^3)	IAE (kmol m^{-3} s)	ISE ($kmol^2$ m^{-6} s)
1	PI-CC	P	100.4396	9.9652	8.4881
2	PID-RM	P	108.3361	9.7175	8.5058
3	**PD-T1FLC**	**P-T1FLC**	99.7704	**9.5105**	8.4505
4	PD-T2FLC	P-T2FLC	99.2400	9.6808	8.4572
5	PID-T1FLC	P-T1FLC	98.5960	9.9505	8.4576
6	**PID-T2FLC**	**P-T2FLC**	**98.5958**	9.7361	**8.3604**

Conclusions

- Cascade control with the primary PID-T2FLC and the secondary P-T2FLC assured the most efficient operation of the investigated tubular chemical reactor.
- Cascade control with the primary PID-T2FLC and the secondary P-T2FLC assured the lowest coolant consumption and the lowest value of the ISE performance index during control of the tubular reactor.
- According to the IAE performance index, cascade control with the primary PD-T1FLC and the secondary P-T1FLC was the best. The second best was CC with the primary PD-T2FLC and the secondary P-T2FLC.
- Based on the comparison of all results, it can be stated that both types of FLCs can be used successfully in cascade control for reaching the goals of control.
- Application of more complicated fuzzy type-2 controllers helped to improve the energetic efficiency of the studied TCR measured by coolant consumption.

Acknowledgments

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