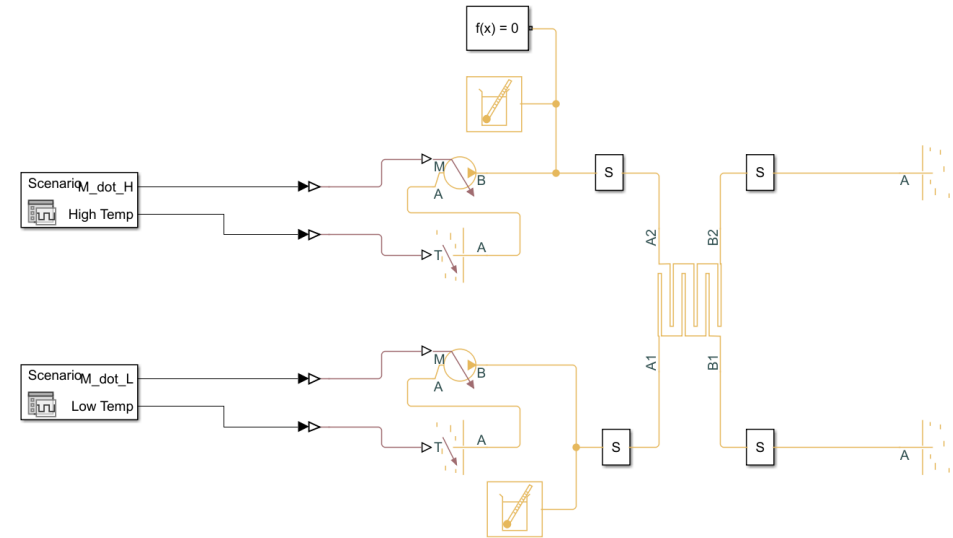


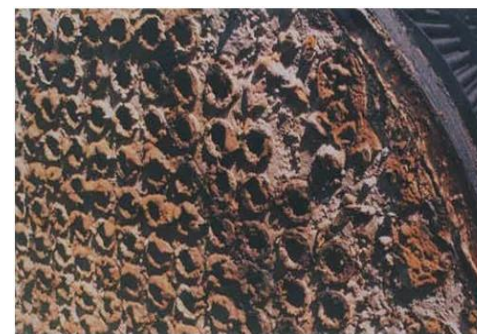
Predictive Maintenance of a Heat Exchanger



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Motivation

- TEMA heat exchangers
 - Over 30 heat exchangers in refinery
 - 200 to 350 heat exchangers in petrochemical plants
- Shell and tube type heat exchangers
- Focus on heat exchanger fouling
- Degrade overall efficiency, increase downtimes
- Implicit equations based on field data



Heat Exchanger Model with E-NTU Method

$$Q_1 = -Q_2 = \epsilon Q_{Max}, 0 < \epsilon < 1$$

$$Q_{Max} = C_{Min} (T_{1,in} - T_{2,in})$$

$$C_{Min} = \min(\dot{m}_1 c_{p,1}, \dot{m}_2 c_{p,2})$$

$$\epsilon = \frac{2}{1 + C_{rel} + \sqrt{1 + C_{rel}^2} \frac{1 + \exp(-NTU \sqrt{1 + C_{rel}^2})}{1 - \exp(-NTU \sqrt{1 + C_{rel}^2})}} \quad [1]$$

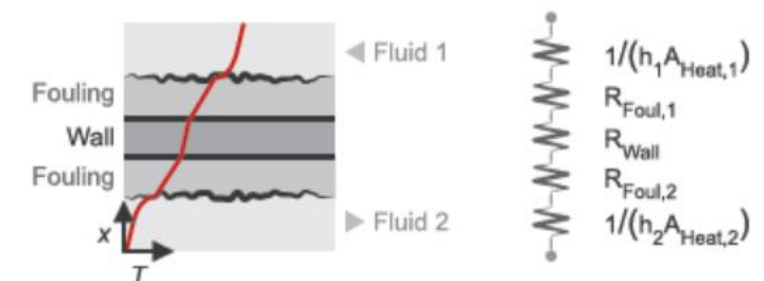
$$C_{rel} = \frac{C_{Min}}{C_{Max}}$$

$$NTU = \frac{1}{C_{Min} R_{Overall}}$$

$$R_{Overall} = \frac{1}{U_{overall} A_{Heat}} = \frac{1}{h_1 A_{Heat,1}} + R_{Foul,1} + R_{Wall} + R_{Foul,2} + \frac{1}{h_2 A_{Heat,2}}$$

- Variables depending on operating conditions and cases – short time process
- Variables depending on deposition of fouling layers – long time process

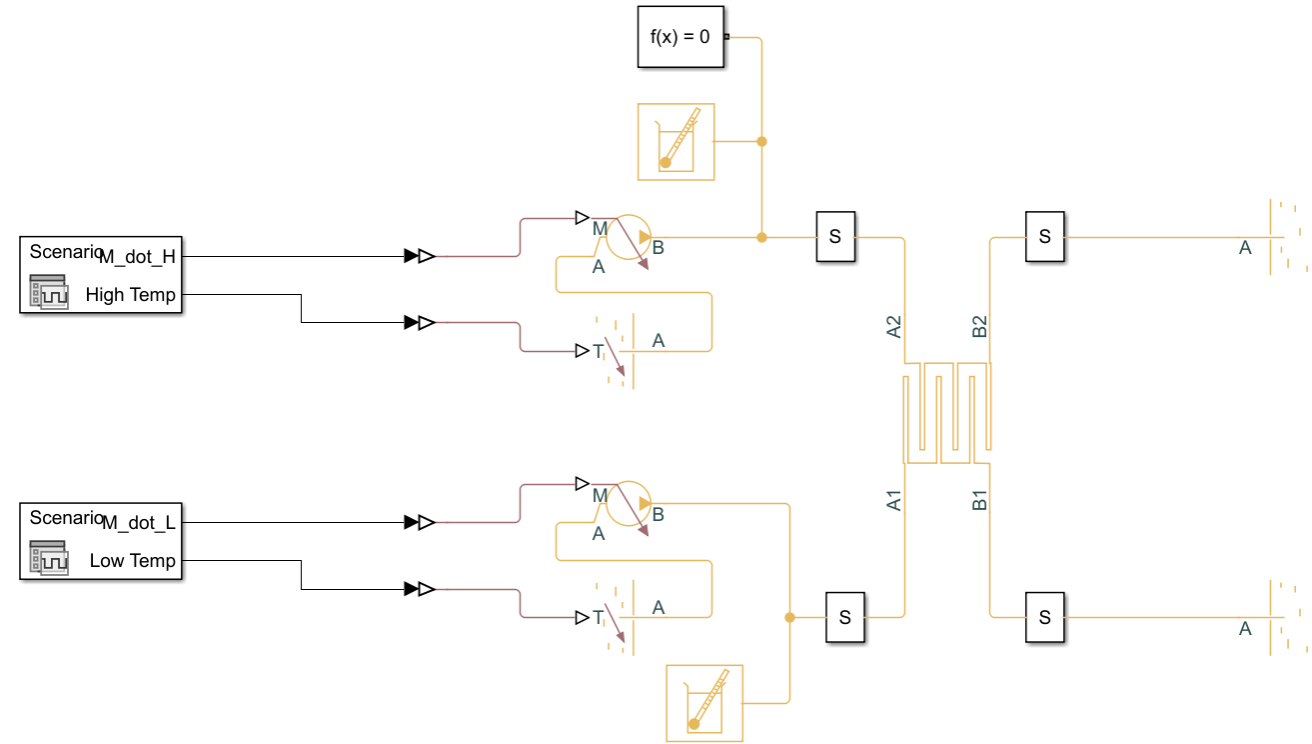
Heat Transfer From Fluid 1 to Fluid 2



[1] Holman, J. P. *Heat Transfer*. 9th ed. New York, NY: McGraw Hill, 2002.

Simscape Model

- Thermal liquid network model
- E-NTU heat exchanger block
- Short time process variables
 - Signal Editor with field data
- Long time process variables
 - Unknown, to be estimated



Block Parameters: Heat Exchanger (TL-TL)

E-NTU Heat Exchanger (TL-TL)

This block models a heat exchanger that transfers heat between two distinct thermal liquid networks. Liquid properties shared between the two thermal liquid networks. Each thermal liquid network must have its own set of liquid properties.

Right-click on the block and select Simscape > Block choices to select between Simple or E-NTU models.

The Simple model uses Specific Dissipation (SD) method to calculate the heat transfer rate. It is defined as the heat transfer rate divided by the difference in inlet temperatures. In E-NTU model, the heat transfer rate is calculated on the Effectiveness-NTU method. The model supports the parallel or concentric flow, shell and tube, cross flow, a heat exchanger configurations.

Ports A1 and B1 are the thermal liquid conserving ports associated with the heat exchanger inlet and outlet for Thermal Liquid 1. Ports A2 and B2 are the thermal liquid conserving ports associated with the heat exchanger inlet and outlet for Thermal Liquid 2.

Settings

Common	Thermal Liquid 1	Thermal Liquid 2	Effects and Initial Conditions
Flow arrangement:	Shell and tube		
Number of shell passes:	1		
Wall thermal dynamics:	Off		
Wall thermal resistance:	wallTherRes <input type="text"/> K/W		

Block Parameters: Heat Exchanger (TL-TL)

E-NTU Heat Exchanger (TL-TL)

This block models a heat exchanger that transfers heat between two distinct thermal liquid networks. Liquid properties are not shared between the two thermal liquid networks. Each thermal liquid network must have its own set of liquid properties.

Right-click on the block and select Simscape > Block choices to select between Simple or E-NTU models.

The Simple model uses Specific Dissipation (SD) method to calculate the heat transfer rate. It is defined as the heat transfer rate divided by the difference in inlet temperatures. In E-NTU model, the heat transfer rate is calculated based on the Effectiveness-NTU method. The model supports the parallel or concentric flow, shell and tube, cross flow, and generic heat exchanger configurations.

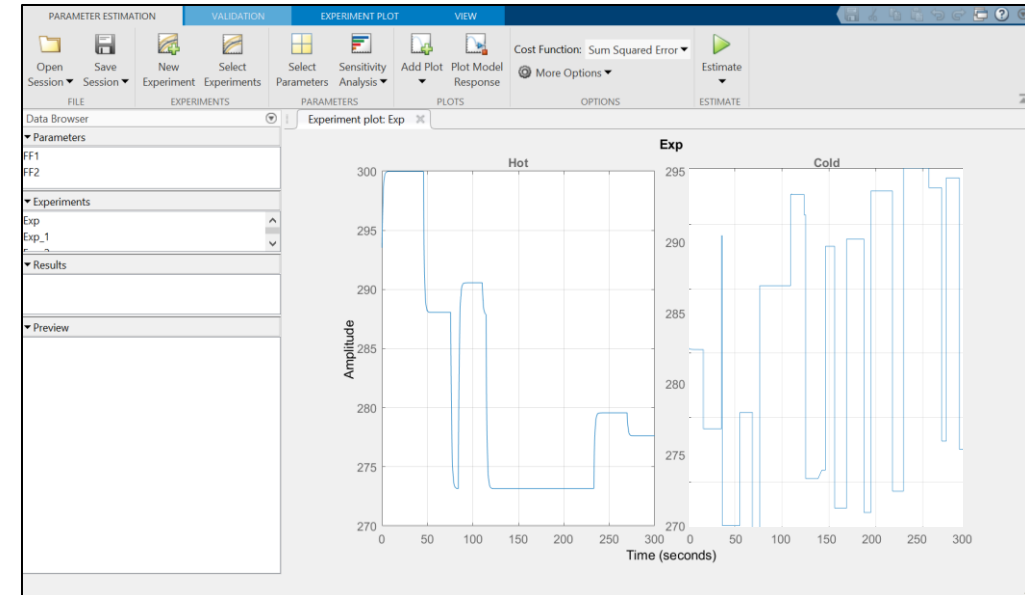
Ports A1 and B1 are the thermal liquid conserving ports associated with the heat exchanger inlet and outlet for Thermal Liquid 1. Ports A2 and B2 are the thermal liquid conserving ports associated with the heat exchanger inlet and outlet for Thermal Liquid 2.

Settings

Common	Thermal Liquid 1	Thermal Liquid 2	Effects and Initial Conditions
Minimum free-flow area:	minFFArea <input type="text"/> m ²		
Hydraulic diameter for pressure loss:	hDiaTube <input type="text"/> m		
Thermal Liquid 1 volume:	0.01 <input type="text"/> m ³		
Laminar flow upper Reynolds number limit:	2000		
Turbulent flow lower Reynolds number limit:	4000		
Pressure loss parameterization:	Constant loss coefficient		
Pressure loss coefficient:	0.1		
Heat transfer parameterization:	Correlation for tubes		
Length of flow path for heat transfer:	lenTube <input type="text"/> m		
Fouling factor:	FF <input type="text"/>		

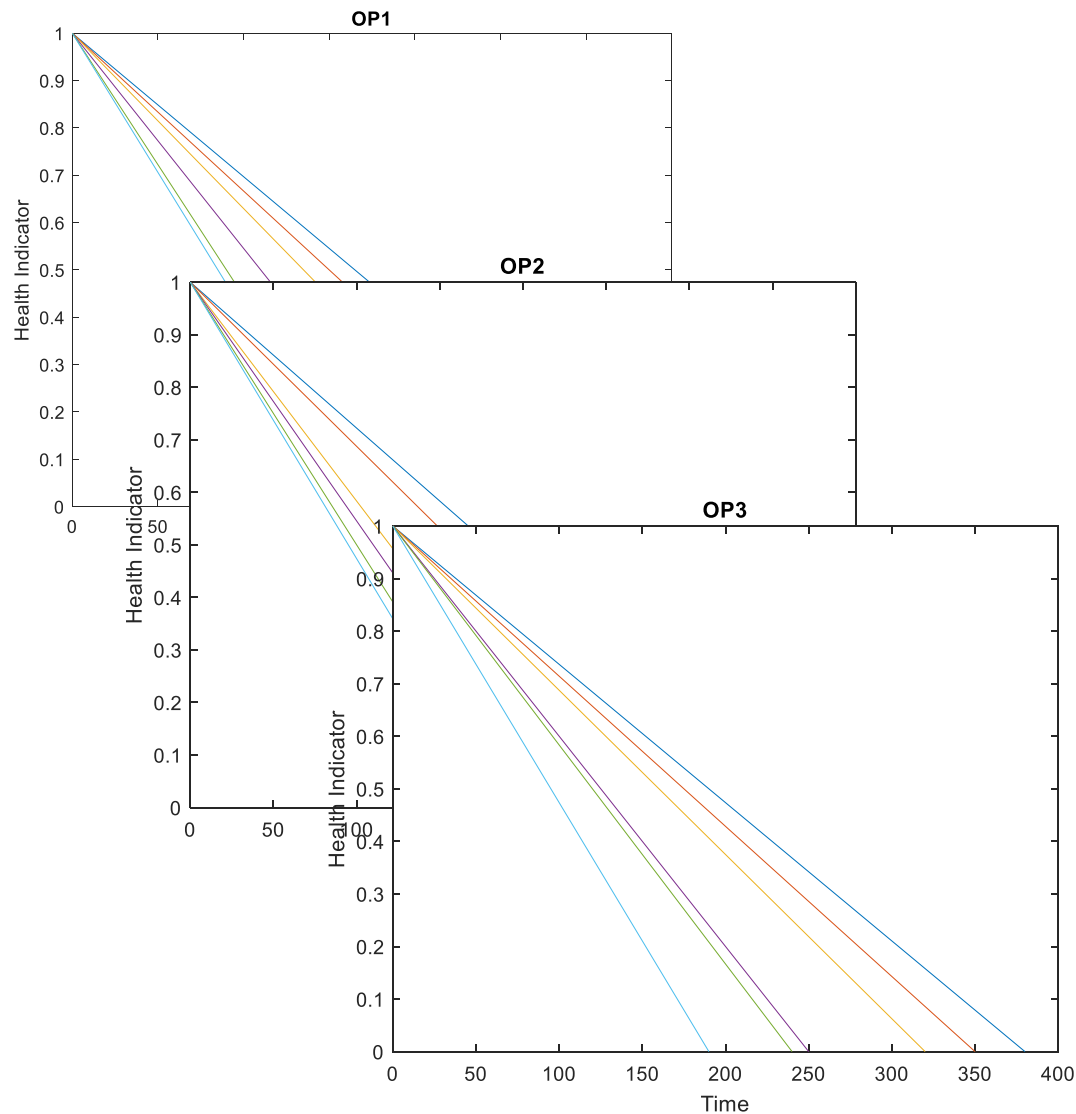
Estimating Fouling Factor With Simulink Design Optimization

- Parameterizing fouling factors
- Separate field data for controlled operating conditions – temperature and mass flow rate
- Iterate fouling factor estimation over time to correlate with efficiency of heat transfer
- Multiple scenarios of operating conditions for fouling factor correction



Fluid (Water)	Fouling Resistances ($m^2 K / KW$)	
Demineralized or distilled	0.009	
Hard	0.043	
Soft	0.017	
Treated cooling tower water	0.034	
Coastal sea water	0.043	
Ocean sea water	0.026	
River water	0.043	
Engine jacket	0.052	
Lubricating oil	0.017	-0.043
Vegetable oil	0.017	-0.052
Organic solvents	0.009	-0.026
Steam	0.009	
General process fluids	0.009	-0.052

Heat Transfer Degradation Simulations and RUL Estimation



- Similarity-based RUL model
- Generation of degradation map
 - Simulating model with degradation time
 - Simulating model with operating conditions
- Parameter estimation of fouling factors
 - Inlet temperature, mass flow rate couples
 - Measurements of heat exchanger outlet temperature
 - Mapping back to degradation map to determine current degradation status

Summary

- Heat exchanger efficiency degradation with fouling
- Identified variables of interests with heat transfer equations
- Modeled heat exchanger with thermal liquid network using Simscape
- Searched ranges of fouling factor related to degradation and operating conditions
- Generated degradation map using simulations under multiple scenarios
- Identified current degradation level by back-calculating fouling factors