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Characterization of a horizontalpipe steam condenser

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ABSTRACT: *The heat transfer via condensation is an outstanding research and teaching subject in the thermodynamics. In this analysis a horizontal pipe steam condenser is described. A parametrical approach was made to investigate the effects of various parameters on the condensation heat transfer. The convective heat transfer in the pipe, the conduction through the pipes metal and the condensation on the pipes surface are considered. The complete heat transfer is implemented in different Matlab procedures. Furthermore a graphical user interface enhances the usability of the program. The program focus on the modifiability of the code, thus the program can be adjusted for numerous cases.*
KEYWORDS:*Heat transfer, condenser, heat pipe.*

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I. INTRODUCTION

The heat transfer on a horizontal pipe steam condenser is characterized by threemain heat transfer mechanisms [1,2,3,4].The first is heat transfer by convection between the cooling liquid in the pipe and thesurface of the pipe.The heat from the hot pipe is transferred to the cooling liquid.The heat transfer coefficient describes the intensity of the heat transfer betweenboth materials. The heat transfer depends on the thermo physical properties of thecooling liquid, the shape of the pipe and the temperature gap between the pipe andthe surface. The thermo physicalproperties are highly dependent on thetemperature this is considered in the temperature-sensitive calculations.The second heat transfer mechanism is the conduction in the pipe. The intensity ofthe heat transfer is affected bythe conductivity and the thickness of the pipe, bothresulting in the heat resistance of the pipe.The third considered effect is the heat transfer via convection between the pipe andthe surrounding condensate film and steam. The refrigerant and its temperature, thecomposition of the 2 phase gas-liquid mixture and the shape and temperature of the pipe have an effect on the heat transfer coefficient and thus on the heat resistance. The film condensation is the prevalent condensation mechanism compared to the drop wise condensation. Dropwise condensation is a much major advantage in heat transfer compared to film condensation. However, the mechanisms to create drop wise condensation are mostly temporary [3] [4]. On account of this the condensation in this elaboration is described as laminar film condensation. The condensate layer in film condensation worsens the heat transfer. Therefore short vertical surface are preferred for a better heat transfer [4]. In this research the heat transfer on a horizontal pipe was investigated.

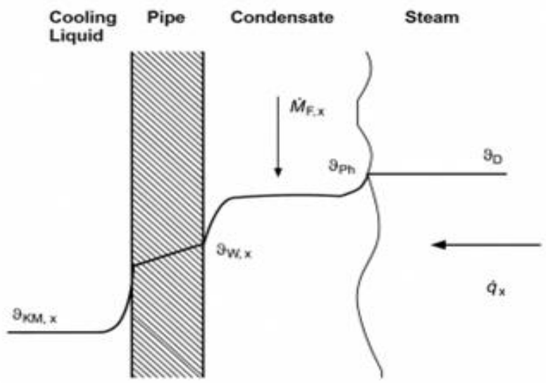

Figure 1. Schematic heat transfer [1]

II.RESEARCH METHODOLOGY

The heat transfer in the pipe is described as in a cylindrical pipe. The flow is considered to be turbulent. The turbulence occurs at very low mass flow of the cooling liquid hence the turbulence is the dominant mechanism. To examine the heat transfer in a pipe the heat transfer coefficient *h* is needed. It can be calculated with the Nusselt Number [1].

$$Nu = \frac{h * d_i}{\lambda}$$

$$Nu = \frac{\frac{\xi}{8}\text{Re}.\text{Pr}}{1 + 12.7\sqrt{\frac{\xi}{8}}(\text{Pr}^{2/3} - 1)}\left[1 + \left(\frac{d}{l}\right)^{2/3}\right]$$

$$\xi = (1.8 * \log \text{Re} - 1.5)^{-2}$$

The boundary conditions for these formulas are:

$$10^4 < Re < 10^6$$

$$0,1 < Pr < 1000$$

The thermo physical properties of the fluid are highly temperature dependent. Thus they have to be calculated depending on the mean temperature T_m.

$$T_m = 0.5 * (T_{in} + T_{out})$$

The heat transfer through the metal pipe is calculated a stationary heat transfer. The conductivity is calculated without the negligible dependency of the pipes conductivity to the temperature. The heat resistance *k*of the pipe is calculated with its thickness $d = (d_{out} - d_{in}) * 0.5$ the conductivity and its inner and outer surface A [2].

$$k = \frac{d \ln\left(\frac{A_{out}}{A_{in}}\right)}{\lambda * (A_{out} - A_{in})}$$

The heat transfer on the surface of the pipe considers the condensation process on the pipe. The condensation is laminar, the flow of the steam is negligible compared to the influence of the gravitational acceleration. The dominant mechanism in applied condensation is the film condensation this is observed in this investigation.

For the calculation of the heat transfer coefficient *h* on the surface of the pipe the following Nusselt Equations [1]

$$Nu = \frac{h * d_i}{\lambda}$$

is used:

$$Nu = 0,959\left[\frac{1 - \left(\frac{\rho_D}{\rho_F}\right)}{\text{Re}_F}\right]^{1/3}$$

$$\text{Re}_F = \frac{\dot{M}_F}{L * \eta_F}$$

The temperature dependent thermo physical properties are calculated at the mean temperature $T_m=0.5*(T_{in}+T_{out})$. The three heat transfer mechanisms are combined to get the overall heat resistance *k* transfer [2].

$$\frac{1}{R*A_{out}}=\frac{1}{h_{in}*A_{in}}+\frac{d\ln\left(\frac{A_{out}}{A_{in}}\right)}{\lambda*(A_{out}-A_{in})}+\frac{1}{h_{out}*A_{out}}$$

The heat transfer through the pipe is equivalent to heat consumed by the cooling liquid.

$$Q=\dot{M}_F*C_p*(T_{out}-T_{in})=k*A*T_{\log}$$

$$T_{\log}=\frac{(T_{steam}-T_{in})-(T_{steam}-T_{out})}{\ln\frac{(T_{steam}-T_{in})}{(T_{steam}-T_{out})}}$$

To calculate the output temperature of the cooling liquid T_{out} this equation is solved using an iterative algorithm. At first T_{out} is assumed and the overall heat resistance *k* and the heat transfer Q are calculated. Using the heat transfer Q the output temperature T_{out} can be calculated. It is adequate to repeat this algorithm three times.

To calculate the temperature dependent thermo physical properties the book VDI Wärmeatlas [1] was used. The calculation is using the following scheme:

$$X=A+B*T+C*T^2+D*T^3+E*T^4$$

The variable X is the temperature dependent thermo physical property. The constant values A to E are listed in the VDI Wärmeatlas [1] for the liquid and the gas phase of each fluid.

Table 1. Temperature Dependent Thermo Physical Properties

Thermo physical property	Unit of measurement	Computing method
Density steam	kg/m³	Ideal gas law
Density liquid	kg/m³	VDI
Dynamic viscosity liquid	kg/(m s)	VDI
Conductivity liquid	W/(m K)	VDI
Heat capacity liquid	J/(kg K)	VDI
Vapor pressure at saturation point	Pa	VDI

The heat transfer on the surface of the pipe is implemented in the Matlab file *surfacepipe.m*the heat transfer in the pipe is implemented in *innerpipe.m*The calculation of the overall heat resistance is done in the file *complete.m*. The visualization of the results functions of Matlab is coded in *visualization.m*. The source code includes comments on every calculation, thus it is easy to understand the programs.

With this modular structure of the program it is easy to modify it for different applications and refrigerants. The program actually includes algorithms for two different refrigerants for condensation on the surface of the pipe, R134a and water. Tetraflouroethane (R134a) is a refrigerant used in fridges and car air conditioning systems.

The program was designed with a graphical user interface which enhances the usability. This program shows the input factor and gives the option to change them. The output is summarized and shown in the GUI. Additionally there is the option to visualize the results. Thus the results of the calculation for different cases can be compared.

Table 2. Input Variables

Input variables	Unit of measurement
Geometry of the pipe	
Diameter	m
Wall thickness	m
Length	m
Conductivity	W/(m K)
Cooling Liquid	
Velocity in the pipe	m/s
Inlet temperature	K
Refrigerant Water or Tetrafluoroethane (R134a)	
Saturation temperature	K

Table 3. Calculation Results

Output	Unit of measurement
Temperature cooling liquid (T_{out})	K
Thermal resistance in pipe	K/W
Thermal resistance pipe	K/(W m^2)
Thermal resistance on pipe	K/W
Heat flow	W
Mass flow condensate	kg/s

III.RESULTS

All the programs where combined in a graphical user interface (GUI) created with the in Matlab included graphical user interface development tool GUIDE. This GUI makes the program user friendly and accessible. With the help of the GUI all the input and output parameters are visual at the first glance.

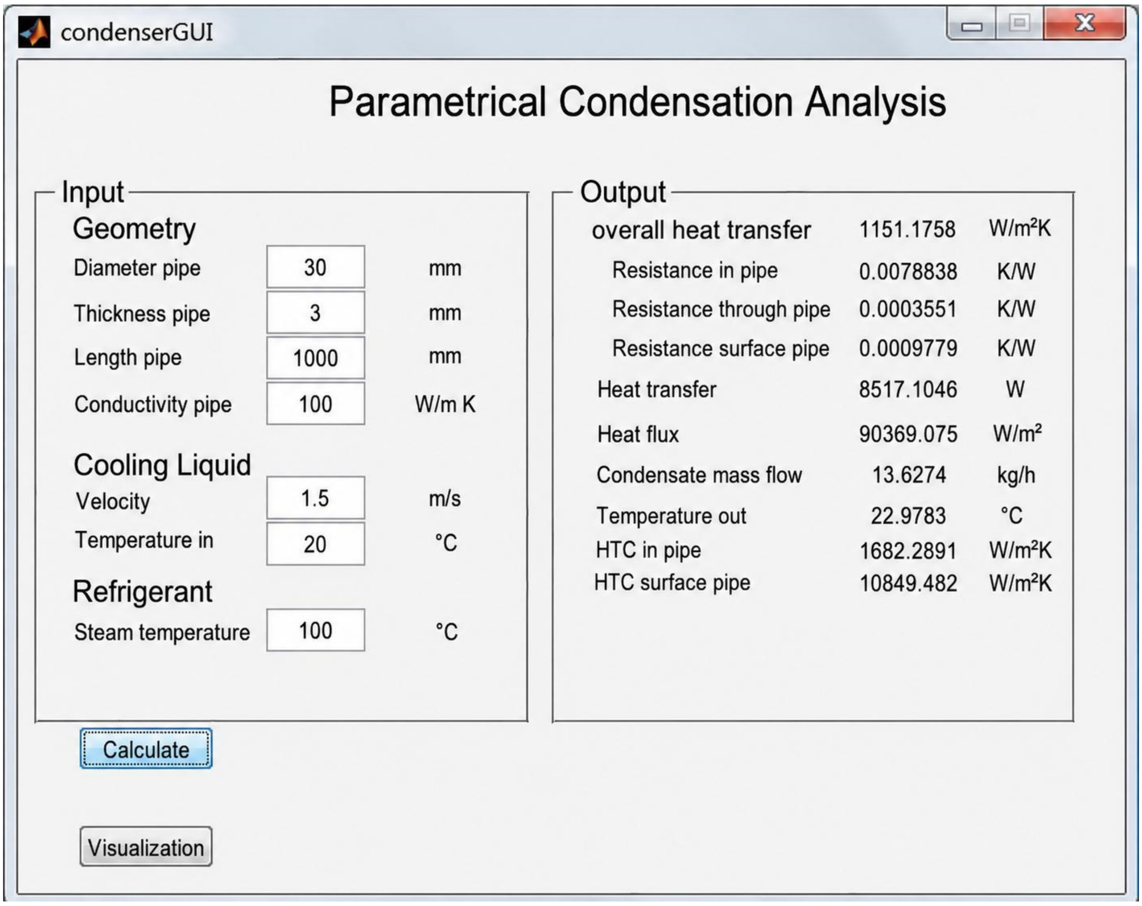

Figure 2. Graphical user interface

The graphical user interface is used to handle the input to the procedures and visualize the output. The calculations are still performed in its respective . m-file. Therewith the program stays modifiable and can easily be customized for different applications. Below some condensing effects are visualized and the effects described.

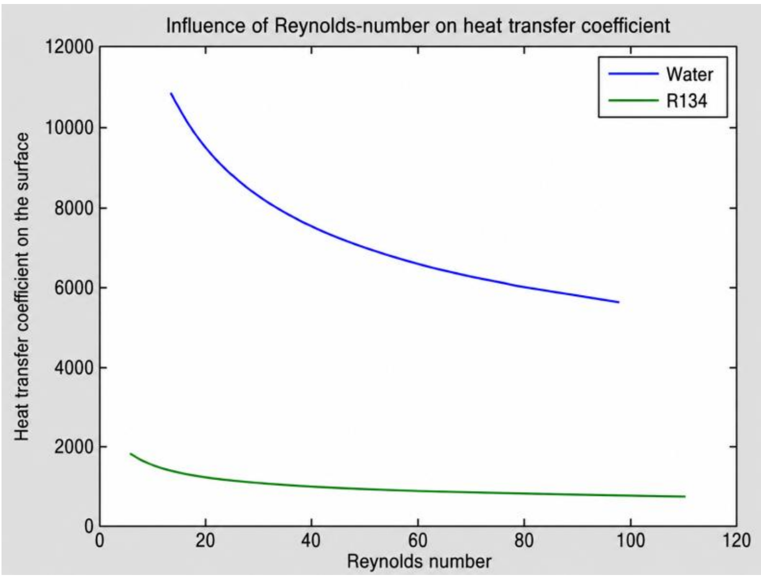

Figure 3. Influence of Reynolds number on heat transfer coefficient

This plot shows how the heat transfer coefficient on the pipe changes with increasing Reynolds number. The Reynolds number on the pipe is calculated using the steam mass flow. With increasing Reynolds number the condensate film on the pipe gets thicker. Since the conductivity of the refrigerant is small, the increasing thickness of the condensate film applies extra heat resistance and thus lowers the intensity of the heat transfer [1]. This effect only applies to laminar condensation. If the condensation is turbulent the heat transfer is increasing with increasing Reynolds numbers.

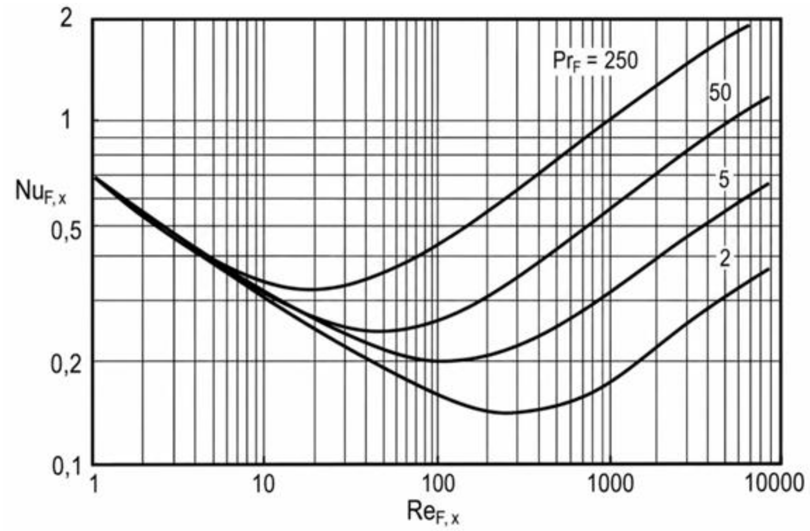

Figure 4. Local nusselt number depending on Reynolds and Prandtl number [1]

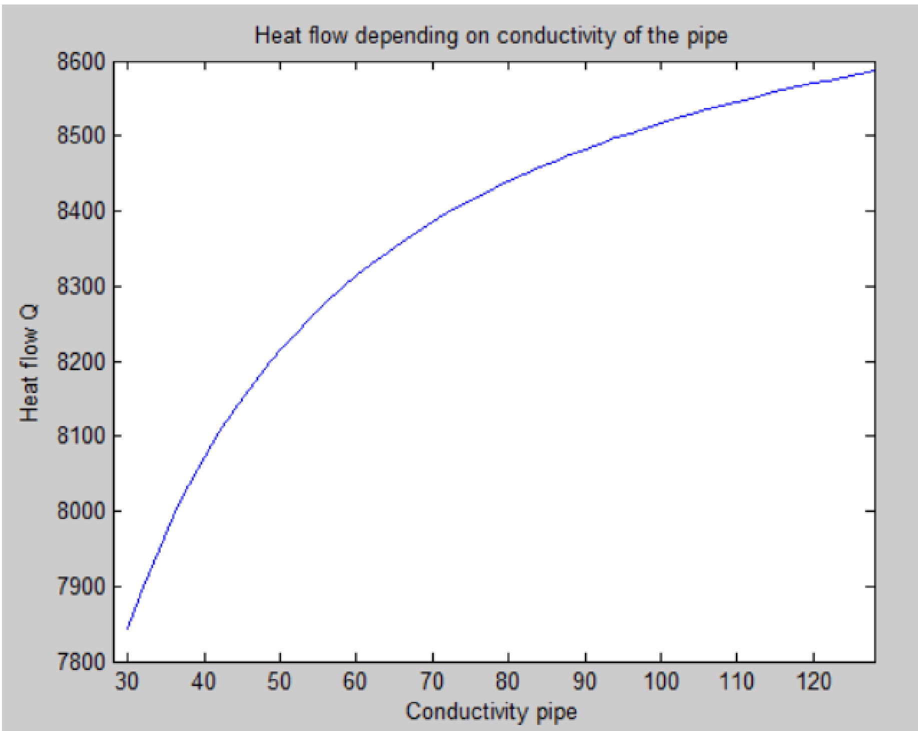

Figure 5. Heat flow depending conductivity of the pipe

In this figure the connection between the overall heat transfer Q and the heat resistance of the pipe is visualized. In general the heat transfer is increasing with increasing conductivity of the pipe. The gradient is high at low conductivity of the pipe but it is getting much lower at higher conductivity. Therefore the improved heat transfer with using different material for the pipe should always be compared to the benefits from the heat transfer of the system. A condenser pipe with very high heat transfer has less effect compared to their higher costs.

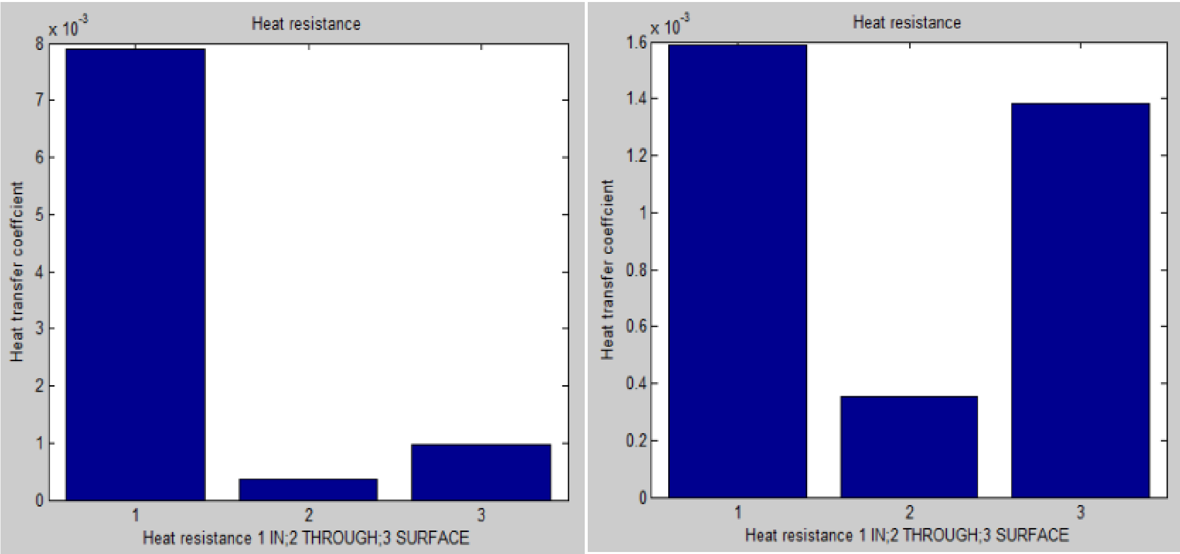

Figure 6. Heat resistance comparison

These figures compare the heat resistance between the three considered heat transfer mechanisms. Using this visualization it is easy to analyze the heat transfer and optimize the condenser. For optimizing the condenser it should be focused on the biggest heat resistance. A few options for optimizing the heat transfer are listed in the table below. In these figures the effect of increasing the velocity of the cooling liquid in the pipe is visualized. In the left picture the heat resistance in the pipe is high because of low velocity 1.5 m/s in the right picture the velocity is increased to 10 m/s hence the heat transfer coefficient is increasing and the resistance lowering while the other thermal resistances stay constant.

Table 4. Optimization

Heat transfer mechanisms	Optimization
In the pipe	• Increasing mass flow• Different cooling liquid• Lower coolant temperature
Through the pipe	• Different pipe material• Thinner pipe
On the pipe	• Different refrigerant• Higher Reynolds number (turbulent flow)• Different pipe geometry

IV. CONCLUSION

The parametrical investigation on steam condensation on a horizontal pipe was implemented in Matlab. Furthermore a graphical user interface was developed to increase the usability of the program.

The implementation shows major coherences and the possibility to modify several parameters. This program can be used for qualifying and quantifying the complete heat transfer on a horizontal pipe steam condenser. With the modular structure of the program it can be modified for several common use cases. Including two different refrigerants and commented source code the program is easy accessible and applicable for different assignments.

Further research possibilities are for instance the implementing of different geometries or other not considered effects of the condensation like turbulent condensation.

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