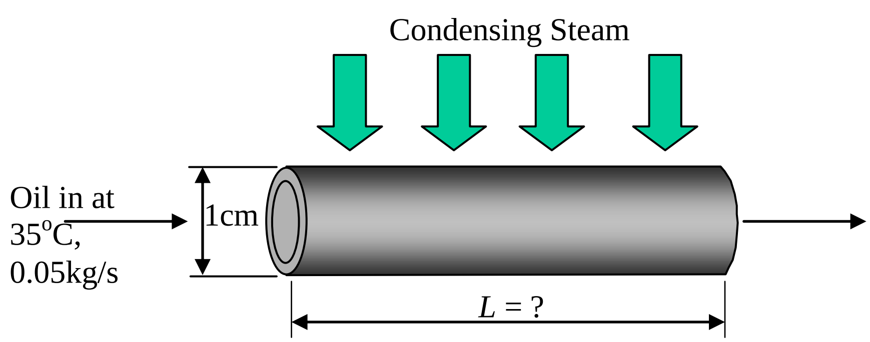
INTERNAL FLOW TEST PROBLEMS

The non-proprietary test problems that have been used to validate some of the capabilities provided in INSTED for the analysis of internal flow are presented in this section. Sufficient information is provided to enable you to complete the test problems without referring to the original sources of the various test problems. These sources are given, as are a few notes to aid in the comparison exercise. Some diagnostic results reported in the sources are given here and compared with INSTED predictions. The percentage difference is given when diagnostic results are presented. You will be expected to have simulated some of these sample problems before attempting to solve more realistic engineering problems. While the capability for analysis of heat transfer in an annulus is provided in the internal flow module, no test problems for the annulus are presented in this chapter. Application-oriented examples for the annulus are presented in the section on concentric tube heat exchangers. The input data for the test problems is contained in the distribution disks. Finally, when differences are indicated between INSTED results and the results from the source, this is often due to the use of simpler and probably less accurate formulas in the source.

Test Problem 1

Problem Statement:



Used engine oil can be recycled by a patented reprocessing system. Suppose that such a system includes a process during which engine oil flows through a 1-cm-ID, 0.02-cm-wall copper tube at the rate of 0.05 kg/s. The oil enters at 35°C and is to be heated to 45°C by atmospheric-pressure steam condensing on the outside. Calculate the length of tube required.

- **Source:**
  Frank Kreith & Mark Bohn. 1993. Fifth Edition. Principles of heat transfer. West Educational Publishing, Boston. Page 393.

- **Comments:**

- In INSTED, choose the 'Tube Length' task and the option to enter mass flow rate (not the velocity).
- From the source: C_p=1964 J/kg K, ρ=876 kg/m^3, k=0.144 W/m K, μ=*0.210* N s /m^2, Pr=28.7.
- Based on the input data, INSTED classifies this problem as Laminar, Developed, Moderate/High Prandtl number'.
- The wall has a fixed temperature. The source assumes the wall temperature is 373.15 K.
- INSTED requires a friction factor. Absolute roughness is obtained from Thaerocomp's database. The smooth pipe option is selected from this database. No additional data is required to obtain a friction factor. The friction factor value suggested at Moody chart calculation is used, which is 2.11.
- Diagnostic results from source areas follows:

Variable	**Kreith**	**INSTED®**	**Difference**
LMTD & (ΔT) (K)	59.9 (N/A)	59.86 (60)	< 1%
L (m)	9.92	9.8847	< 1%
h (W/m^2K)	52.7	52.7	< 1%
q (LMTD) (W)		979.72	
q (ΔT) (W)	983	982.00	< 1%
f	N/A	2.11	

- Explanation of difference in solution between source and INSTED:
  a. is potentially more accurate than the Dittus and Boelter formula used in the source.
  b. No allowance is made for the friction in this source, whereas, in INSTED, a friction factor is required.

  Name of data file: Krbohn.393

Test Problem 2

- **Problem Statement:**
  Air at 2 atm and 200°C is heated as it flows through a tube with a diameter of 1 in (2.54 cm) at a velocity of 10 m/s. Calculate the heat transfer per unit length of tube if a constant-heat-flux condition is maintained at the wall and the wall temperature is 20°C above the air temperature, all along the length of the tube.

- **Source:**
  J.P. Holman. 1990. Heat Transfer. McGraw-Hill Publishing Company, New York. Second Edition, Page 293.

- **Comments:**
  - In INSTED, choose the 'heat flow rate' task and the option to enter velocity (not mass flow rate).
  - Since the outlet temperature is given, a good approach for this problem will be to first estimate it (using INSTED), by evaluating properties at the inlet temperature. A more representative bulk temperature can then be calculated and used to evaluate properties. However, the restriction on wall temperature (20°C above local bulk temperature) makes this impossible to do. What we have done is to simply set the inlet and outlet bulk temperatures to the same value of 200°C.
  - Per unit length (that is, 1 m) is considered.
  - Data in source are used. Thaerocomp's database is not needed.
  - From the source: C_p=1025 J/kg K, ρ=1.493 kg/m^3, k=0.0386 W/m K, μ=2.57X10^{-5} N s /m^2, Pr=0.681
  - Based on the input data, INSTED classifies this problem as 'Turbulent, Developed, Moderate/High Prandtl number'.
  - INSTED requires a friction factor. Absolute roughness is obtained from Thaerocomp's database. The smooth pipe option is selected from this database. No additional data is required to obtain a friction factor. The friction factor value suggested at Moody chart calculation is used, which is 0.02793.
  - Diagnostic results from source

Variable	**Holman**	**INSTED®**	**Difference**
Nu	42.67	39.38	< 8%
LMTD & (ΔT) (K)	59.9 (N/A)	59.86 (60)	< 1%
h (W/m^2K)	64.85	64.85	<8%
q' (ΔT) (W/m)	103.5	95.52	< 8%
f	N/A	0.02793	

  - Explanation of difference in solution between source and INSTED:
    a. is potentially more accurate than the Dittus and Boelter formula used in the source.
    b. No allowance is made for the friction in this source, whereas, in INSTED, a friction factor is required.

    Name of data file: Holman.293

Test Problem 3

- **Problem Statement:**
  Water at 60°C enters a tube of 1-in (2.54 cm) diameter at a mean flow velocity of 2 cm/s. Calculate the exit water temperature if the tube is 3.0 m long and the wall temperature is constant at 80°C.
- **Source:**
  J. P. Holman. 1990. Heat Transfer. McGraw-Hill Publishing Company, New York, Second Edition, Page 294. This is also the same as example 5.2 (page 224) of Basic Heat Transfer by Frank Kreith & William Z. Black, Harper & Row Publishers, 1980.
- **Comments:**
  - In INSTED, choose the 'outlet temperature' task and the option to enter velocity (not mass flow rate).
  - Data in source are used. Thaerocomp's database is not needed.
  - From the source: C_p=4180 J/(kg K), ρ=985 kg/m^3, k=0.651 W/m K, μ=4.71X10^{-4} N s /m^2, μ_b=5.55X10^{-4} N s /m^2, μ_w=3.55X10^{-4} N s /m^2, Pr=3.02.
  - Based on the input data that excludes the effect of viscosity on temperature, INSTED classifies the problem as 'Laminar, Entry, Moderate/High Prandtl number' when the effect of viscosity at the wall is included. In INSTED, wall viscosity changes the problem type only in laminar, non-annulus cases.
  - INSTED requires a friction factor. Absolute roughness is obtained from Thaerocomp's database. The smooth pipe (glass) option is selected from this database. No additional data is required to obtain a friction factor. The friction factor value suggested in INSTED is used, which is 0.06024.

  Diagnostic results from source are as follows:

Variable	**Holman**	**INSTED®**	**Difference**
Nu	5.816	5.817	<1%
h (W/m^2K)	149.1	149.1	<1%
$T_{b,mean}$	66°C	65.99°C	<1%

  - Name of data file: Holman.294.

Test Problem 4

- **Problem Statement:**
  An electronic device is cooled by water flowing through capillary holes drilled in the casing as shown in the Figure below. The temperature of the device casing is constant at 353 K. The capillary holes are 0.3 m long and 2.54 X 10^{-3} m in diameter. If water enters at a temperature of 333 K and flows at a velocity of 0.2 m/s, calculate the outlet temperature of the water.

- **Source:**

  Frank Kreith & Mark Bohn. 1993. Fifth Edition. Principles of heat transfer. West Educational Publishing, Boston. Page 403.
- **Comments:**
  - In INSTED, choose the 'outlet temperature' task and the option to enter velocity (not mass flow rate).
  - Units are SI.
  - Data in source are used. INSTED's database is not needed.
  - From the source: C_p=4181 J/(kg K), ρ=983 kg/m^3, k=0.658 W/m K, μ=4.72X10^{-4} N s /m^2, μ_w=3.52X10^{-4} N s /m^2, Pr=3.0.
  - Based on the input data that excludes the effect of viscosity on temperature, INSTED classifies the problem as "Laminar, developed, moderate/high Prandtl number." When the effect of viscosity at the wall is included, the classification changes to "laminar, entry length, moderate/high Prandtl number." In INSTED, wall viscosity changes the problem type only in laminar, non-annulus cases.
  - INSTED requires a friction factor. Absolute roughness is obtained from Thaerocomp's database. The smooth pipe (glass) option is selected from this database. No additional data is required to obtain a friction factor. The friction factor value suggested in INSTED is used, which is 0.06049.

  Diagnostic results from source.

Variable	**Kreith**	**INSTED®**	**Difference**
Nu	5.67	5.805	<3%
h (W/m^{2}K)	1479	1503.76	<2%
$T_{b,out}$ (K)	345 .00	371.476	<8%

  - Name of data file: Krbohn.403

Test Problem 5

- **Problem Statement:**

  A 2.0-cm-diameter tube having a relative roughness of 0.001 is maintained at constant wall temperature of 90°C. Water enters the tube at 40°C and leaves at 60°C. If the entering velocity is 3 m/s, calculate the length of tube necessary to accomplish the heating.
- **Source:**

  J. P. Holman. 1990. Heat Transfer. McGraw-Hill Publishing Company, New York. Second Edition, Page 297.
- **Comments:**
  - In INSTED, choose the "Length of Tube (Duct)" task and the option to enter velocity (not mass flow rate).
  - The given inlet and outlet temperatures are used as the (respective) bulk temperatures.
  - Data in source are used. Thaerocomp's database is not needed.

- From the source: C_p=4174 J/kg K, ρ=978 kg/m^3, k=0.664 W/m K, μ=4.0X10^{-4} N s /m^2, μ_b=5.55X10^{-4} N s /m^2, μ_w=2.81X10^{-4} N s /m^2, Pr=2.54.
- Based on the input data, INSTED classifies the problem as turbulent, with moderate/high Prandtl number. Internally, INSTED forces a fully developed flow whenever the task is to find tube length, as in the present case.
- INSTED requires a friction factor. Absolute roughness is obtained by multiplying the given roughness by the diameter of tube. This value is entered as user-specified absolute roughness, in the Moody chart environment. No additional data is required to obtain a friction factor. The friction factor value suggested in INSTED is used, which is 0.02145.
- Diagnostic results from source are as follows:

Variable	**Holman**	**INSTED®**	**Difference**
L (m)	1.40	1.4558	< 4%
Nu	666.8	633.93	< 5%
h (W/m^{2}K)	22,138.0	21029.9	5%
q (LMTD) (W)		75316.5	
q (ΔT) (W)	77,812.0	76947.2	< 2%
f	.0218	.02145	< 2%

- Explanation of difference:
  Different formulas are used in INSTED and the source. The source is based on Petukhov formula, whereas Gnielinski-type formula is used in INSTED. Gnielinski's approach to calculate in INSTED has been discussed under 'Internal Flow'.
- Name of data file: Holman.297

Test Problem 6

- **Problem Statement:**
  A liquid metal flows at a mass rate of 3 kg/s through a constant heat flux 5-cm-i.d tube in a nuclear reactor. The fluid at 473 K is to be heated with the tube wall 30 K above the fluid temperature. Determine the length of the tube required for a 1-K rise in bulk fluid temperature, using the following properties:
  ρ = 7.7 x 10^3 kg/m^3
  v = 8.0 x 10^{-8} m^2/s
  c_p = 130 J/(kg K)
  k = 12 W/mK
  Pr = 0.011
- **Source:**
  Frank Kreith & Mark Bohn. 1993. Fifth Edition. Principles of heat transfer. West Educational Publishing, Boston. Page 422.

- **Comments:**
  - In INSTED, choose the 'length of tube (duct)' task and the option to enter velocity (not mass flow rate).
  - The inlet and outlet temperatures (473 K and 474 K) are used as the (respective) bulk temperatures.
  - This is a liquid metal flow, since Prandtl number is not greater than 0.05. The condition of constant surface heat flux is used.
  - Data in source are used. Thaerocomp's database is not needed.
  - Based on the input data, INSTED classifies the problem as turbulent, developed, liquid metal.
  - INSTED requires a friction factor. Absolute roughness is obtained from Thaerocomp's database, using the smooth wall (glass) option. No additional data is required to obtain friction factor. The friction factor value suggested in INSTED is used, which is 0.01706.
  - Diagnostic results from source:

Variable	**Kreith**	**INSTED®**	**Difference**
LMTD & (ΔT) (K)	(30)	29.497 (29.5)	(< 2%)
L (m)	0.0307	.02894	< 6%
h (W/m^2K)	2692.00	2908.41	< 9%
q' (LMTD) (W/m)		389.96	
q (ΔT) (W)	390.00	390.00	0%
f	N/A	2.11	

  - Explanation if difference:
    a. different formulas are used in INSTED and the source for the calculation of Nusselt number.
    b. friction factor is not used in source
  - Name of data file: Kreith.247