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# A Numerical Estimation of Heat Loss of a Pipe Burrowed in a Soil Using ANSYS Steady-State Thermal Analysis

**Nikolay Lyan**
**110160908**

# Abstract

In this paper, it will be shown how to use an engineering simulation software to solve theoretical and practical tasks. In particular, the heat loss of the pipeline buried at a depth of 6 meters underground will be estimated. As an engineering simulation software, due to its speed and accuracy, it was decided to use ANSYS and its Steady-State Thermal Analysis. The calculations will be made in three variations: using coarse, medium and fine mesh densities. In conclusion, an estimate of the error with respect to the analytical method will be presented using each option.

# Introduction

As a task, problem #5.5 from the “Fundamentals of Heat and Mass Transfer” book was given. The problem states:

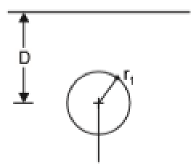
> *A pipe carrying oil and having a diameter of 0.6 m is buried in soil of conductivity 0.6W/mK at a depth of 6m. The surface temperature of the pipe is 80°C. The surface of the soil is at –10°C. Determine the heat loss from the pipe for 1 m length. If the velocity is 2 m/s and the density is 900 kg/m3 and specific heat 2000 J/kgK determine the temperature drop in flow through a distance of 100 m.*

Given the specifics of the work performed, the second part of the problem was omitted. For solving this problem, 2D simplification and triangles method mesh will be made.

**Analytical solution of the given problem using the shape factor formulation:**

$$Q = kS\Delta T$$

$k = 0.6\ W/mK$ $\quad r = 0.3\ m$ $\quad D = 6\ m$ $\quad L = 100\ m$ $\quad \Delta T = 80 - (-10) = 90°$




Cylinder in semi infinite medium, Length L

$L >> r \qquad S = \frac{2\pi L}{\cosh^{-1}(D/r)}$

$D > 3r \qquad S = \frac{2\pi L}{\ln(2D/r)}$

$D >> r \qquad S = \frac{2\pi L}{\ln(L/r)\left[\frac{\ln(L/D)}{\ln(L/r)}\right]}$

Since $L \gg r$, $S = \frac{2\pi L}{\cosh^{-1}(D/r)}$

$Q = 0.6 \cdot \frac{2\pi \cdot 100}{\cosh^{-1}(6/0.3)} \cdot 90 = \mathbf{9199.26\ W}$

## Setup

Firstly, it is need to draw a test section for the problem. For a precise solution it was decided to use a rectangle with sides of 200D and 100D + 6 meters (depth), where D is the diameter of pipe (0.6 meters).

Which results to a 120m X 66m test section:

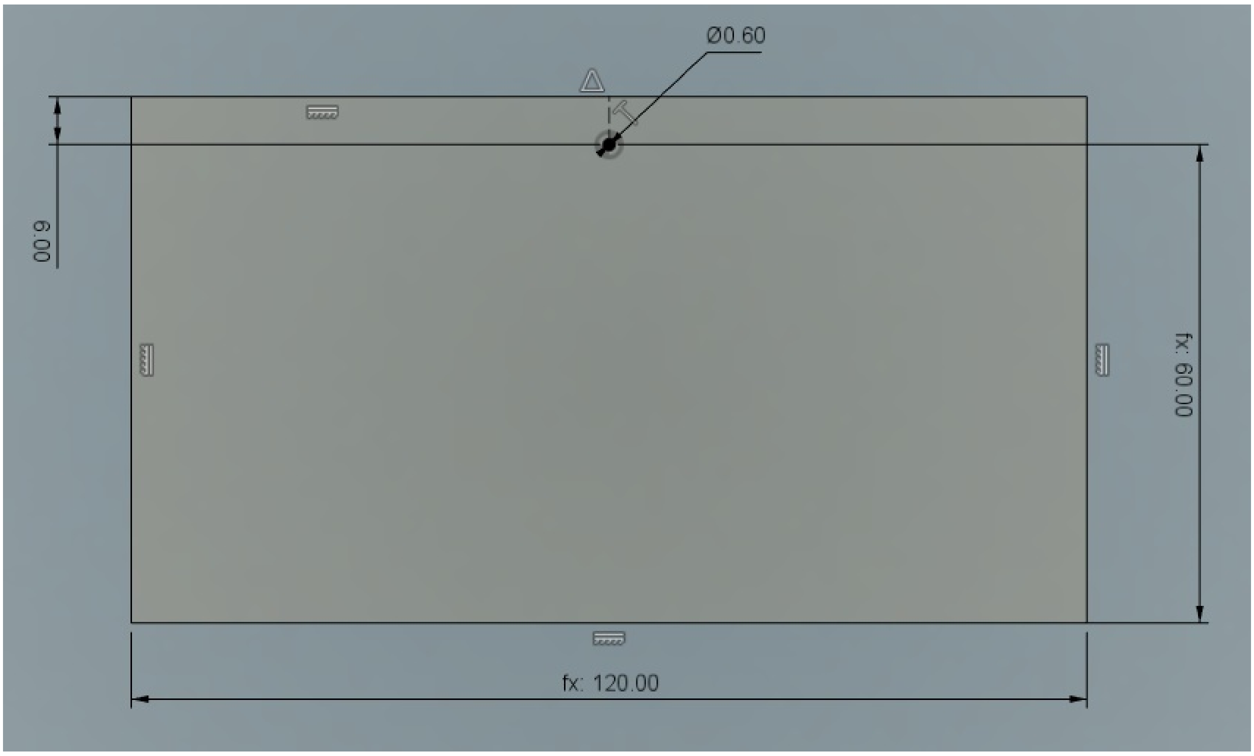



Fig.1 Sketch of the test section in Autodesk Fusion 360

Second step is to set up steady-state thermal model in ANSYS:

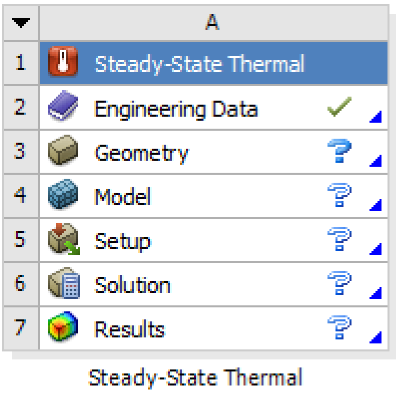



Fig.2 Steady-state thermal model

And set given thermal property of the soil (*conductivity = 0.6W/mK*):

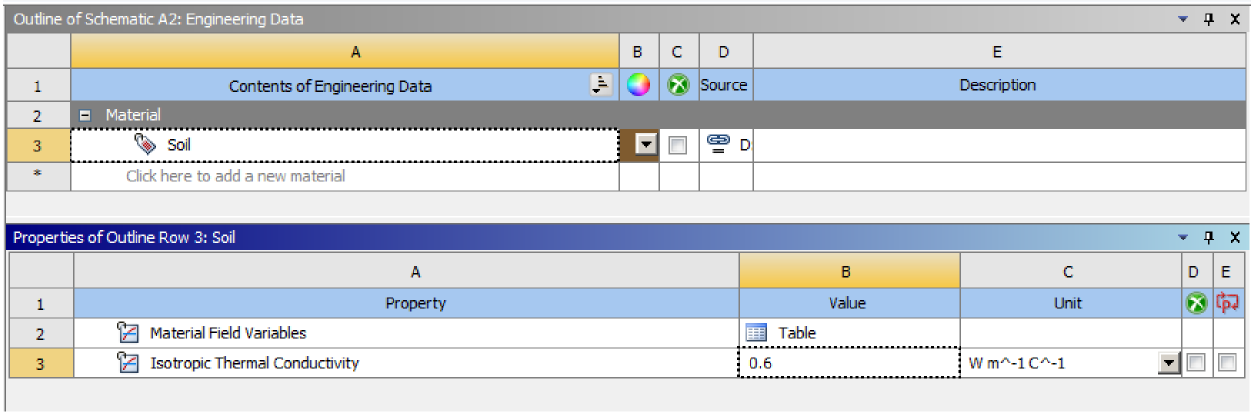



Fig.3 Material properties section

Importing 2D surface from Fusion 360 to SpaceClaim:

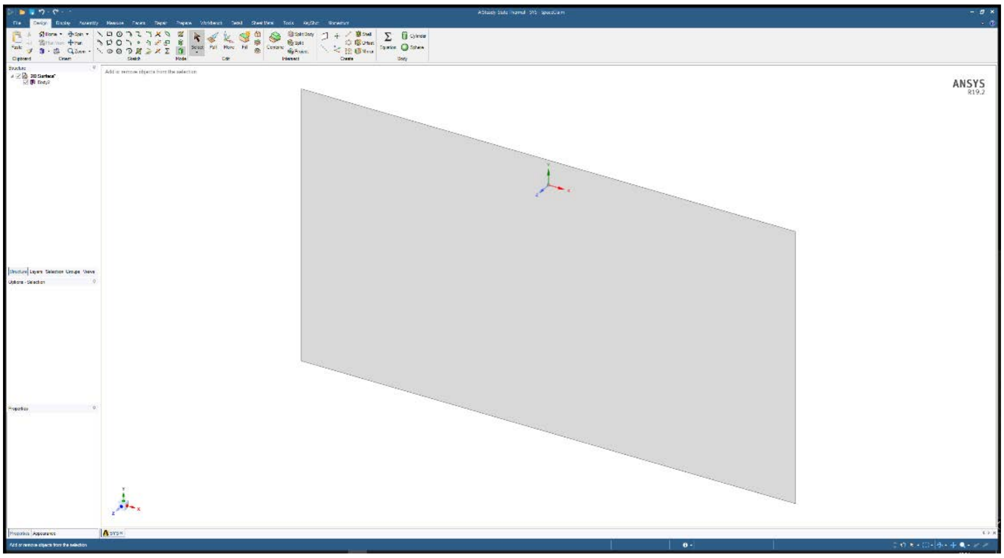



Fig.4 SpaceClaim interface

Changes made to the structure of the model:

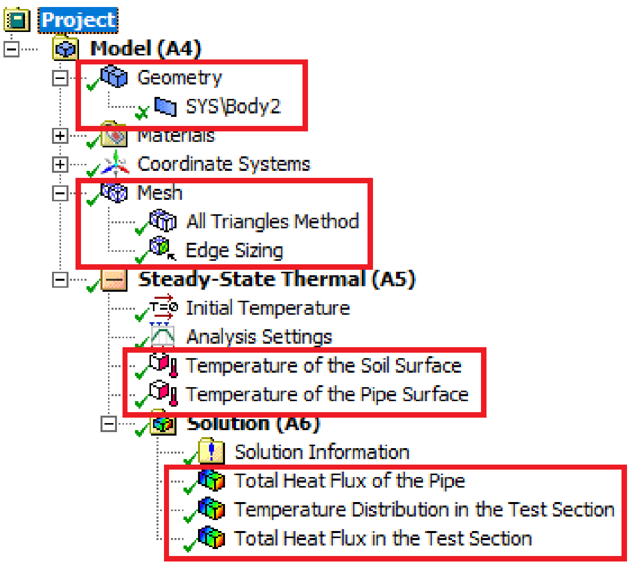
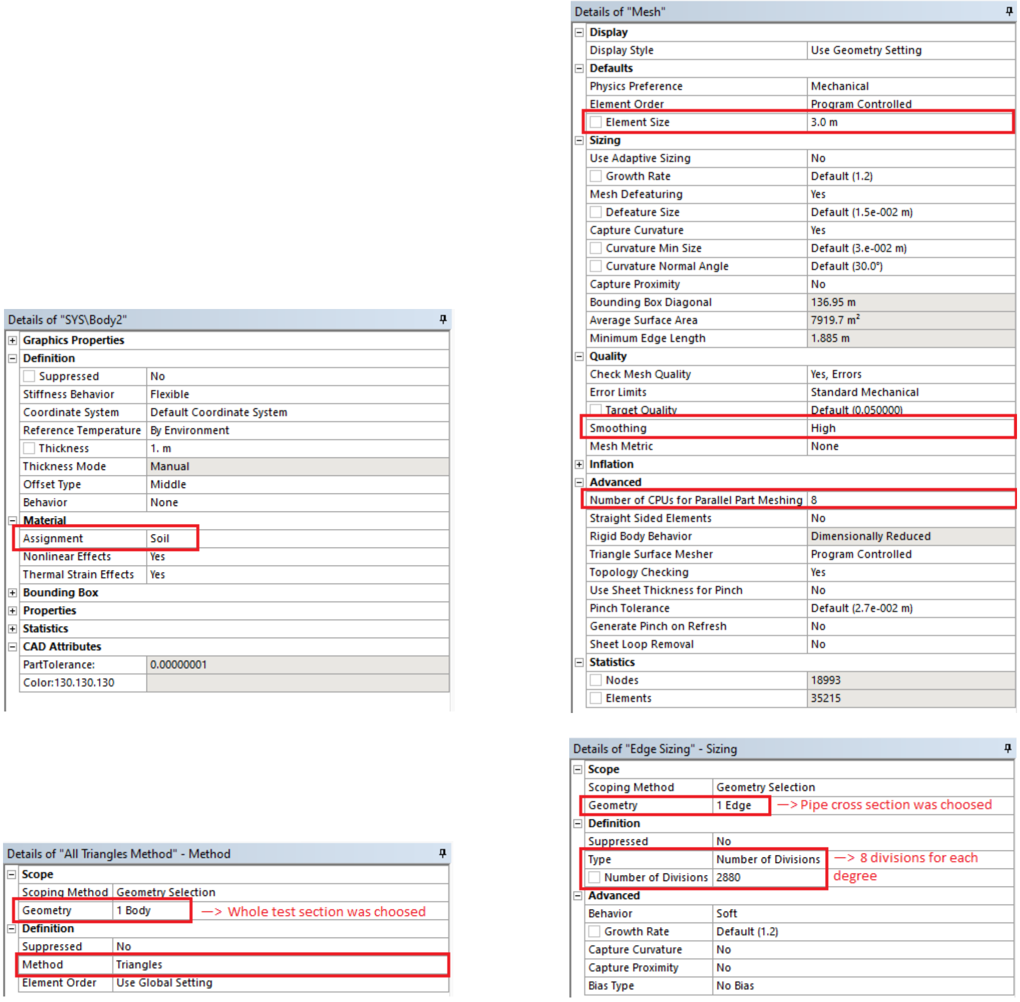



Fig.5 Marked was added or changed



Details of "SYS\Body2"

| | |
|---|---|
| **Graphics Properties** | |
| **Definition** | |
| Suppressed | No |
| Stiffness Behavior | Flexible |
| Coordinate System | Default Coordinate System |
| Reference Temperature | By Environment |
| Thickness | 1. m |
| Thickness Mode | Manual |
| Offset Type | Middle |
| Behavior | None |
| **Material** | |
| Assignment | Soil |
| Nonlinear Effects | Yes |
| Thermal Strain Effects | Yes |
| **Bounding Box** | |
| **Properties** | |
| **Statistics** | |
| **CAD Attributes** | |
| PartTolerance: | 0.00000001 |
| Color:130.130.130 | |

Details of "All Triangles Method" - Method

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 1 Body —> Whole test section was choosed |
| **Definition** | |
| Suppressed | No |
| Method | Triangles |
| Element Order | Use Global Setting |

Details of "Mesh"

| | |
|---|---|
| **Display** | |
| Display Style | Use Geometry Setting |
| **Defaults** | |
| Physics Preference | Mechanical |
| Element Order | Program Controlled |
| Element Size | 3.0 m |
| **Sizing** | |
| Use Adaptive Sizing | No |
| Growth Rate | Default (1.2) |
| Mesh Defeaturing | Yes |
| Defeature Size | Default (1.5e-002 m) |
| Capture Curvature | Yes |
| Curvature Min Size | Default (3.e-002 m) |
| Curvature Normal Angle | Default (30.0°) |
| Capture Proximity | No |
| Bounding Box Diagonal | 136.95 m |
| Average Surface Area | 7919.7 m² |
| Minimum Edge Length | 1.885 m |
| **Quality** | |
| Check Mesh Quality | Yes, Errors |
| Error Limits | Standard Mechanical |
| Target Quality | Default (0.050000) |
| Smoothing | High |
| Mesh Metric | None |
| **Inflation** | |
| **Advanced** | |
| Number of CPUs for Parallel Part Meshing | 8 |
| Straight Sided Elements | No |
| Rigid Body Behavior | Dimensionally Reduced |
| Triangle Surface Mesher | Program Controlled |
| Topology Checking | Yes |
| Use Sheet Thickness for Pinch | No |
| Pinch Tolerance | Default (2.7e-002 m) |
| Generate Pinch on Refresh | No |
| Sheet Loop Removal | No |
| **Statistics** | |
| Nodes | 18993 |
| Elements | 35215 |

Details of "Edge Sizing" - Sizing

| | |
|---|---|
| **Scope** | |
| Scoping Method | Geometry Selection |
| Geometry | 1 Edge —> Pipe cross section was choosed |
| **Definition** | |
| Suppressed | No |
| Type | Number of Divisions —> 8 divisions for each degree |
| Number of Divisions | 2880 |
| **Advanced** | |
| Behavior | Soft |
| Growth Rate | Default (1.2) |
| Capture Curvature | No |
| Capture Proximity | No |
| Bias Type | No Bias |

Fig.6 Marked was changed

8 divisions for each degree was set in order to achieve the better mesh and a precise solution.

Further changes are just pointers to the parts of the test section, where “pipe” is the cross-section edge of the “circle” in the test section and “soil” is its upper bounding edge.

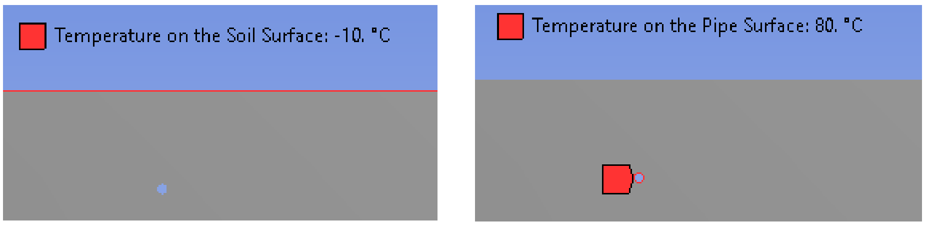



Fig.7 Initial conditions for temperature

# Summary of the applied changes

## Model

- **Geometry**
  - **SYS\Body *(Test section)***
    - **Thickness** => 1.0 m
    - **Assignment** => Soil

- **Mesh**
  - **Method** => All Triangles Method
    - **Geometry** => 1 Body *(Test section)*
    - **Method** => Triangles

  - **Sizing** => Edge Sizing
    - **Geometry** => 1 Edge *(Pipe cross-section)*
    - **Type** => Number of Divisions
    - **Number of Divisions** => 2880

  - **Element size** => 3.0 m
  - **Smoothing** => High

- **Steady-State Thermal**
  - **Temperature** *(of the Soil Surface)*
    - **Geometry** => 1 Edge *(Test sections upper edge — Soil Surface)*
    - **Magnitude** => -10 C

  - **Temperature** *(of the Pipe Surface)*
    - **Geometry** => 1 Edge *(Pipe cross-section — Pipe Surface)*
    - **Magnitude** => 80 C

- **Solution**
  - **Total Heat Flux** *(Distribution on the Pipe Surface)*
    - **Geometry** => 1 Edge *(Pipe cross-section — Pipe Surface)*

  - **Temperature** *(Distribution in the Test Section)*
    - **Geometry** => 1 Body *(Test section)*

  - **Total Heat Flux** *(Distribution on the Test Section)*
    - **Geometry** => 1 Body *(Test section)*

# Results and Solutions

## Mesh

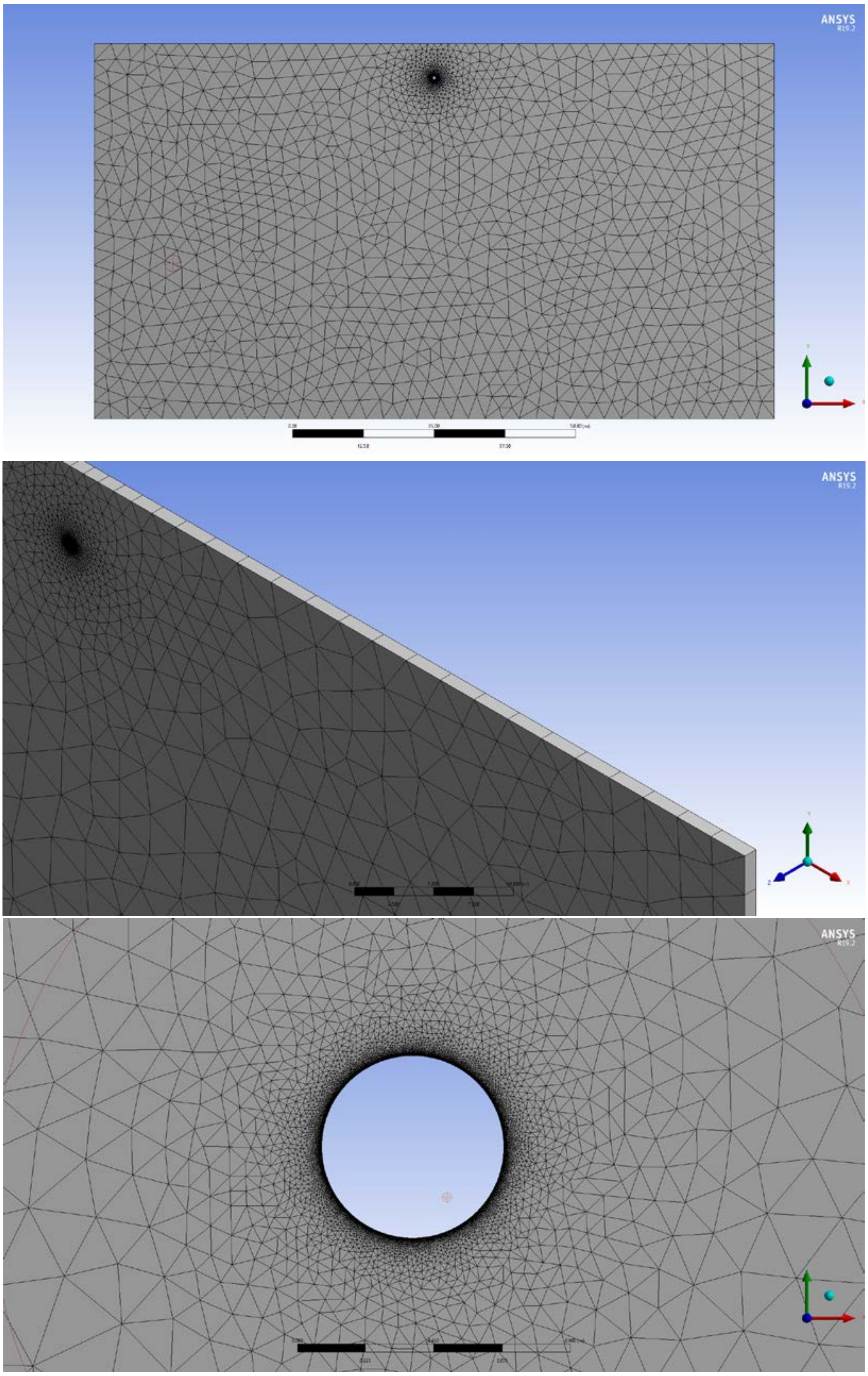



Fig.8 Obtained mesh

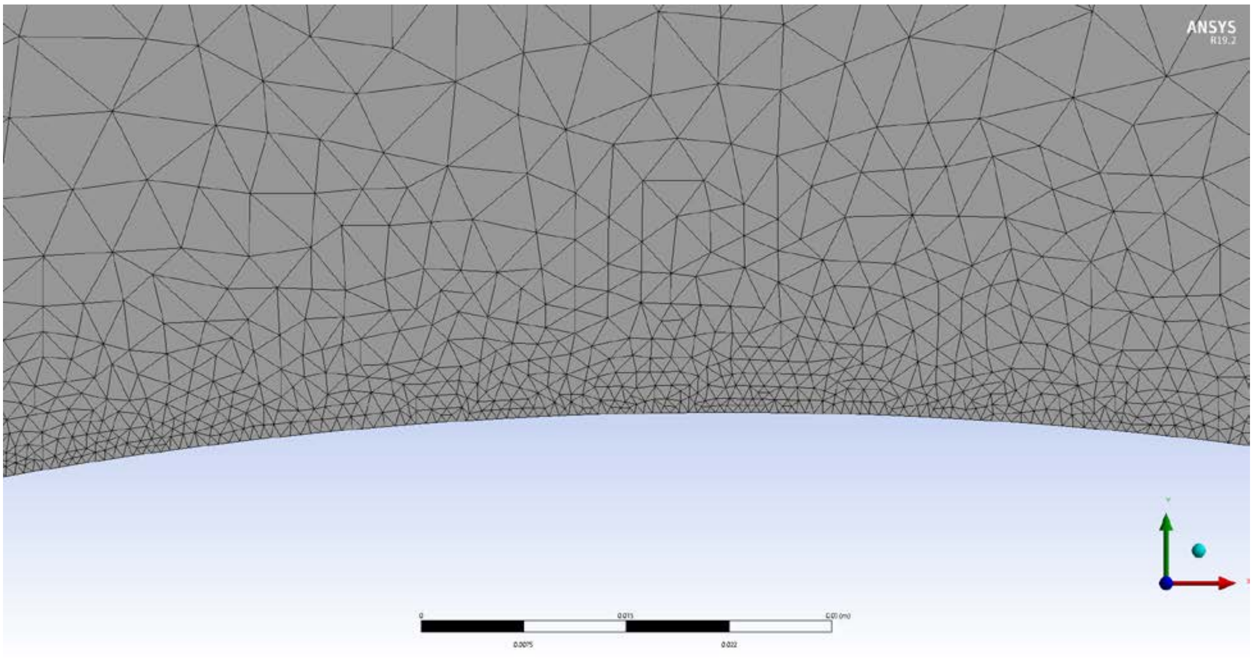



Fig.9 Obtained mesh (continue of Fig.8)

## Solution

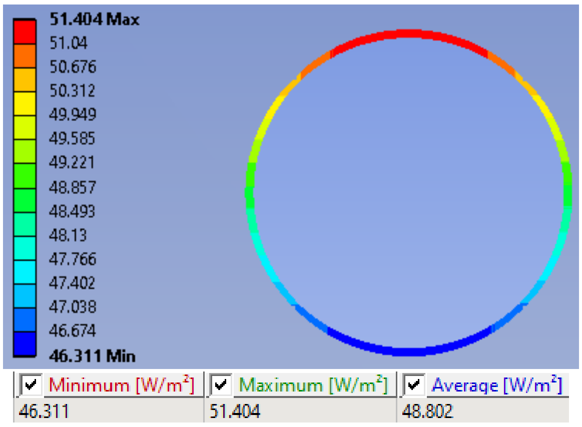



Fig.10 Total heat flux distribution on the pipe surface (simplified)

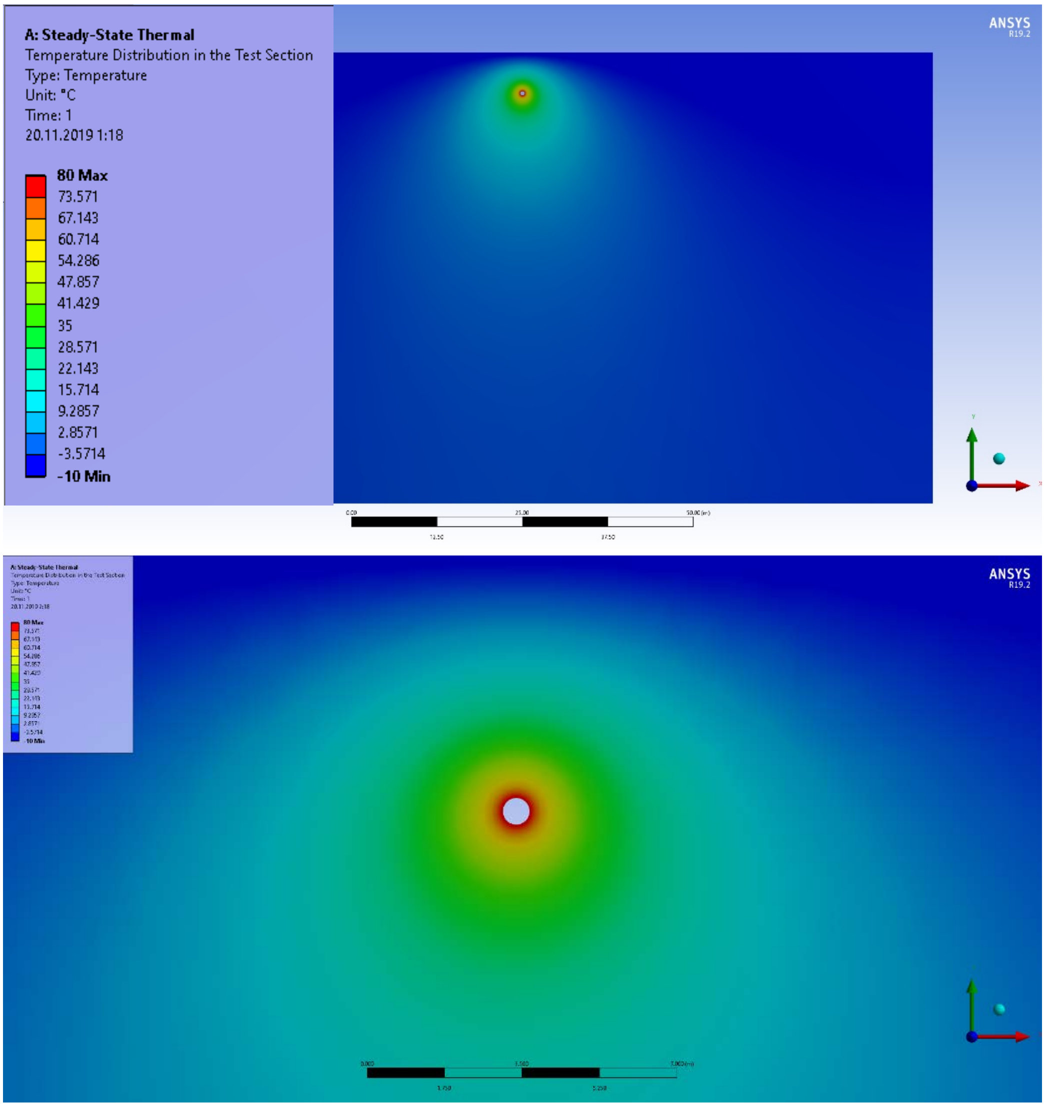



Fig.11 Total temperature distribution in the test section

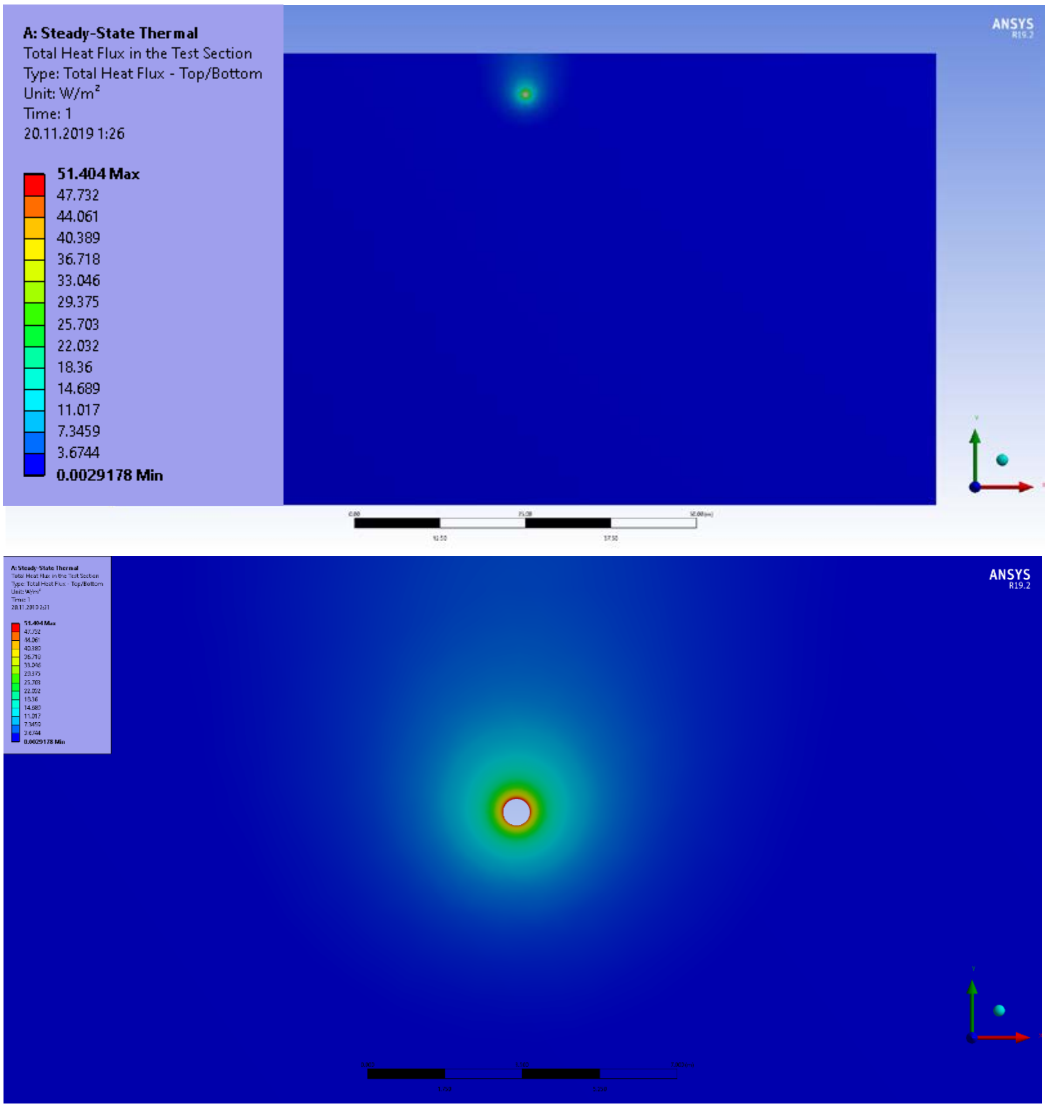


Fig.12 Total heat flux distribution in the test section

Average of total heat flux on the pipe: $\dot{q} = \mathbf{48.802\ W/m^2}$

Resulting heat loss of 100 meters pipe: $Q = \dot{q} \cdot \pi DL = 48.802 \cdot 60\pi = \mathbf{9198.96\ W}$

Analytical heat loss: $Q = \mathbf{9199.26\ W}$

Accuracy: $\frac{9198.96}{9199.26} \cdot 100\% = \mathbf{99.997}\%$

**Technical information:**

- **Number of Elements:** 35215
- **Total CPU time:** 1.750 seconds

Assuming performed mesh «fine», continue with performing simulation with «medium» and «coarse» meshes, so variants will be as follow:

- **«Fine» Mesh**
  - **Sizing** => Edge Sizing
    - **Number of Divisions** => 2880
  - **Element size** => 3.0 m
  - **Smoothing** => High

- **«Medium» Mesh**
  - **Sizing** => Edge Sizing
    - **Number of Divisions** => 288
  - **Element size** => 5.0 m
  - **Smoothing** => Medium

- **«Coarse» Mesh**
  - **Sizing** => Edge Sizing
    - **Number of Divisions** => 30
  - **Element size** => 10.0 m
  - **Smoothing** => Low

## Mesh comparison:

«Fine» «Medium» «Coarse»

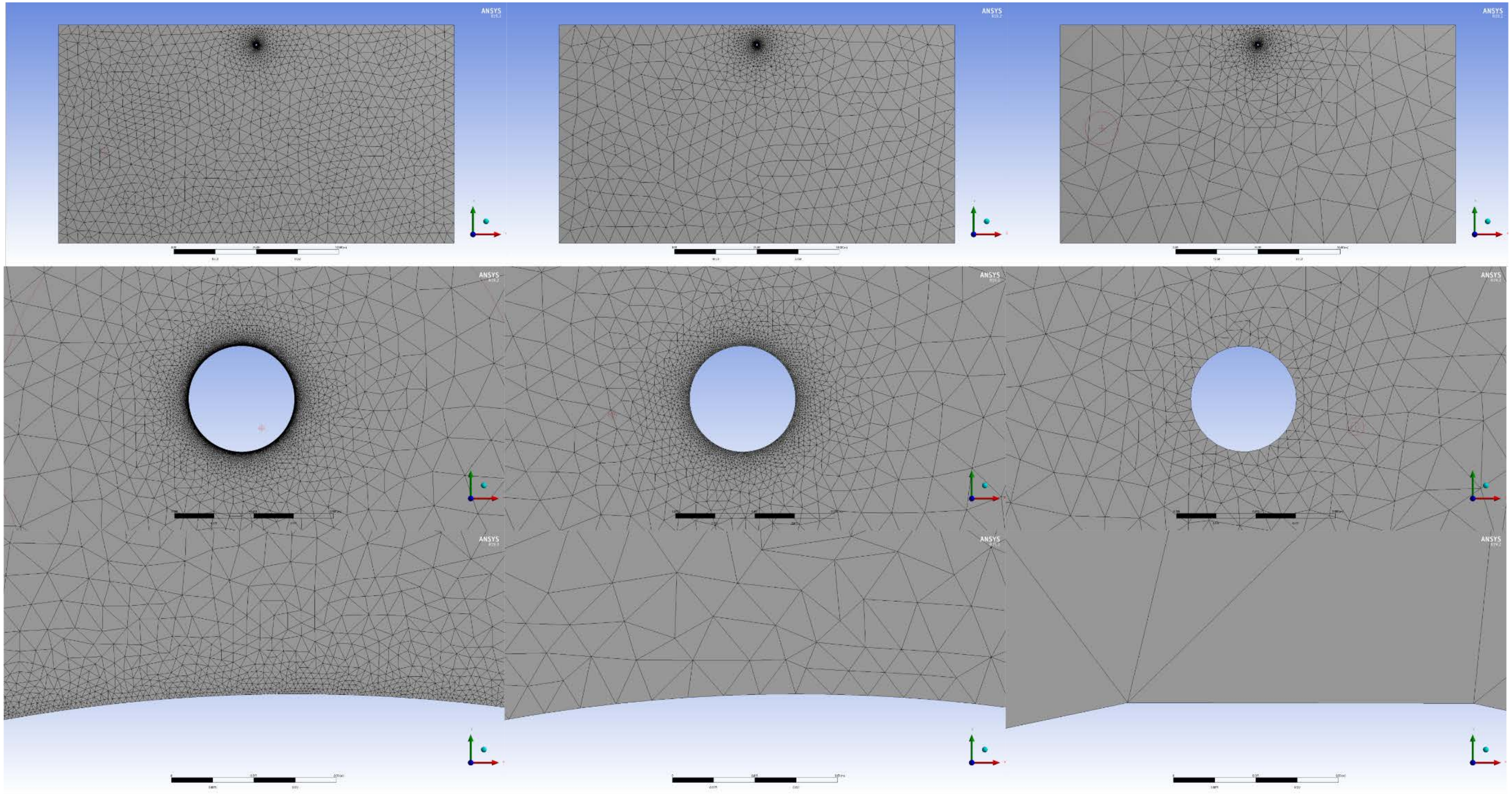


Fig.13 Mesh variants

## Comparison of the total heat flux distribution on the pipe surface

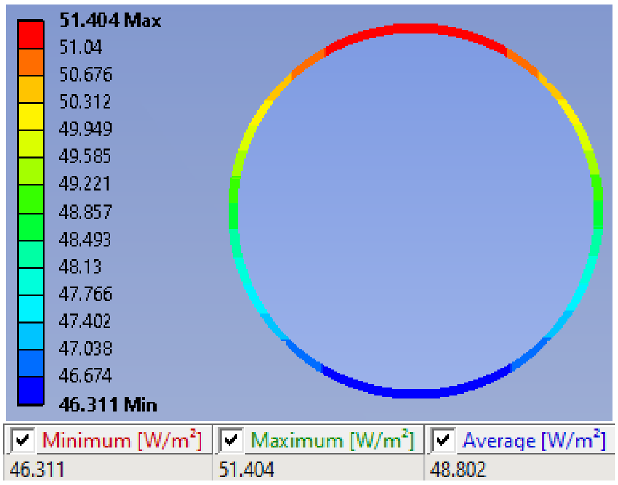



Fig.14 «Fine»

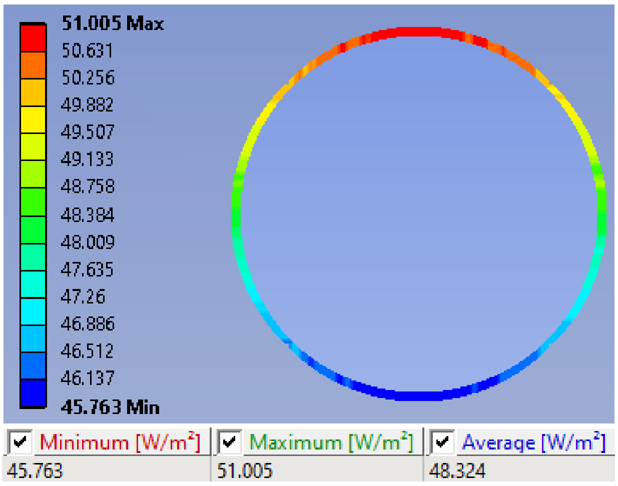



Fig.15 «Medium»

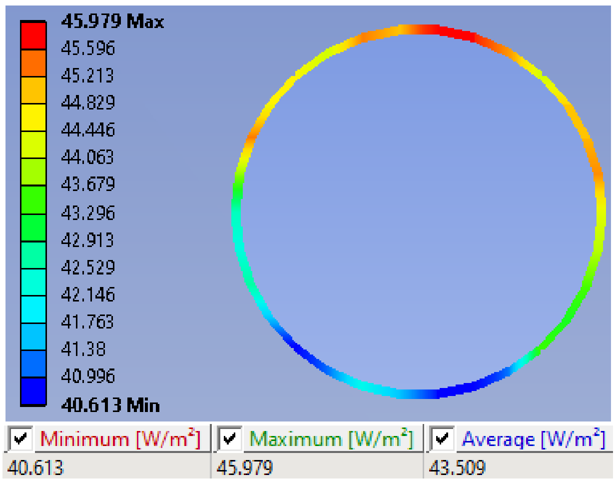



Fig.16 «Coarse»

## Comparison of the temperature distribution in the test section

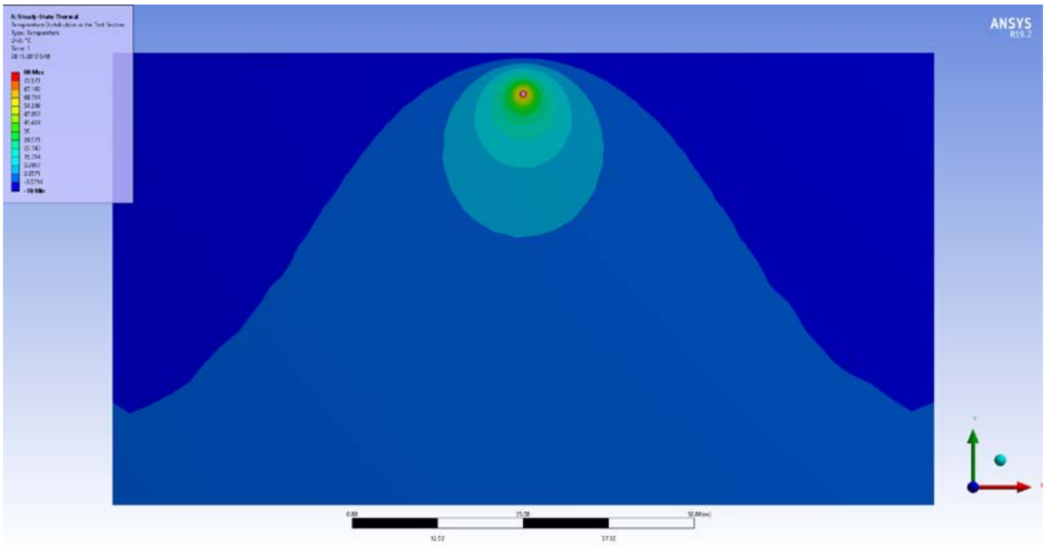



Fig.17 «Fine»

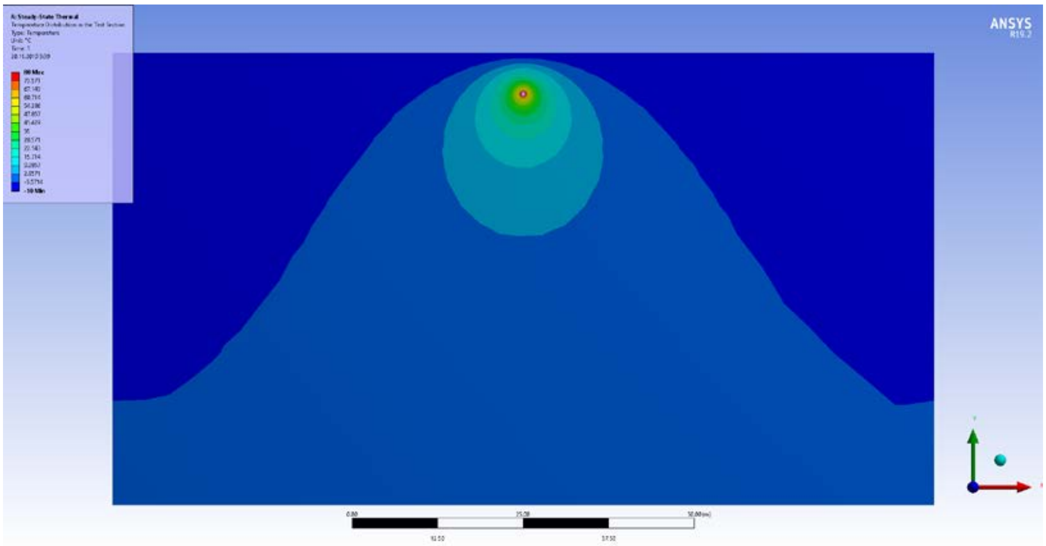



Fig.18 «Medium»

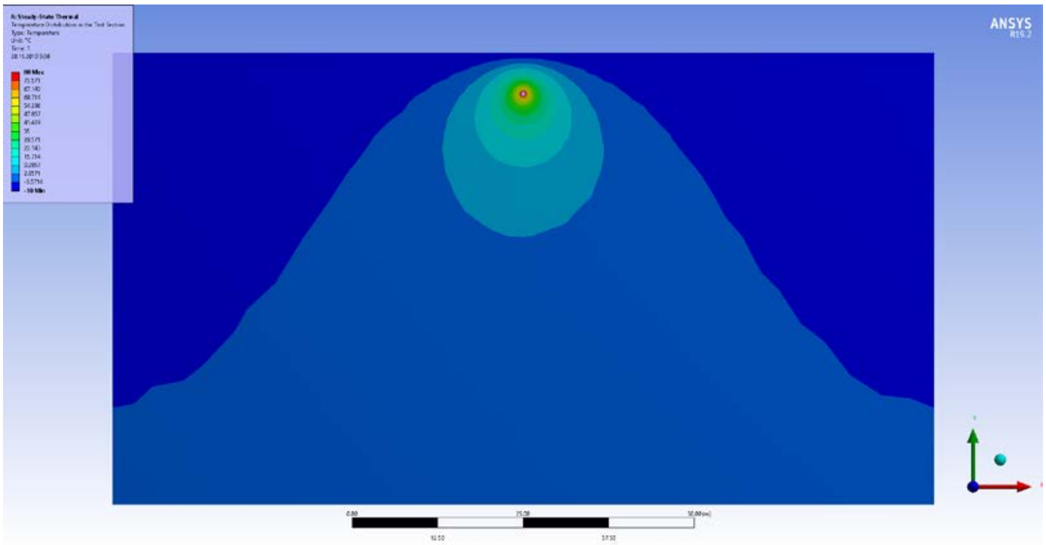



Fig.19 «Coarse»

«Fine» «Medium» «Coarse»

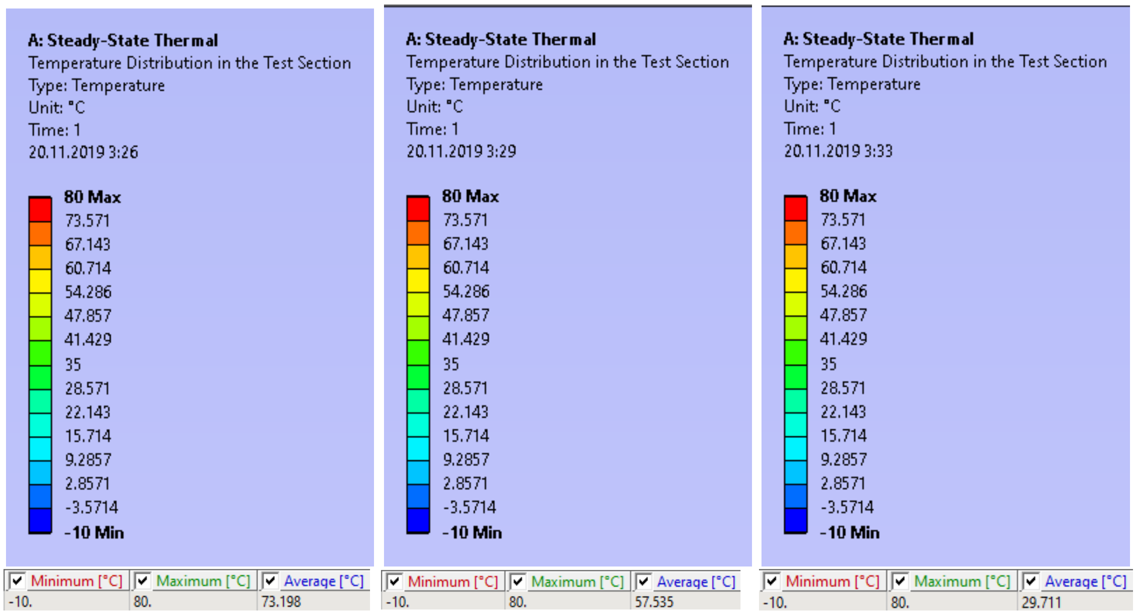



Fig.20 Temperature graphs

## Comparison of the total heat flux distribution in the test section

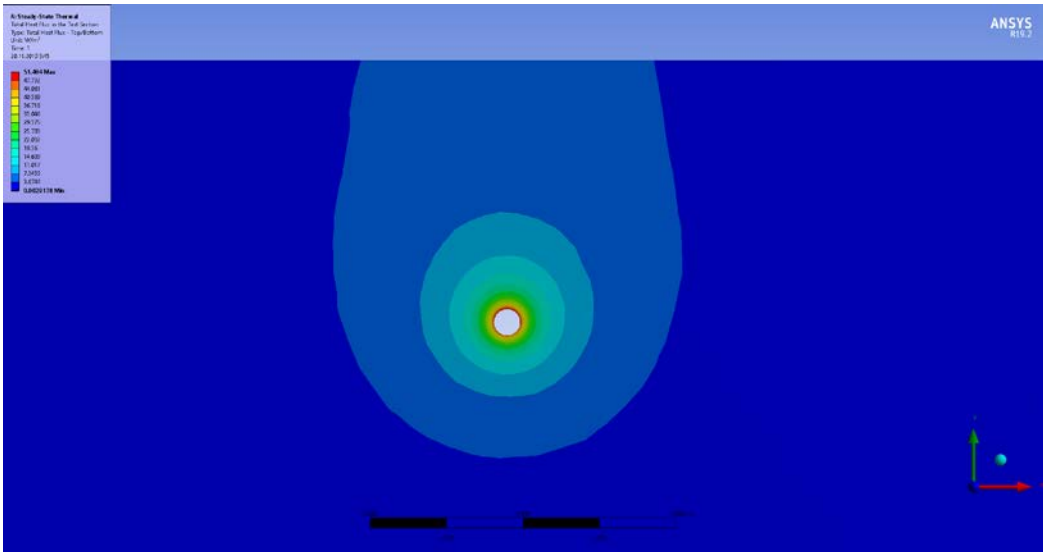


Fig.21 «Fine»

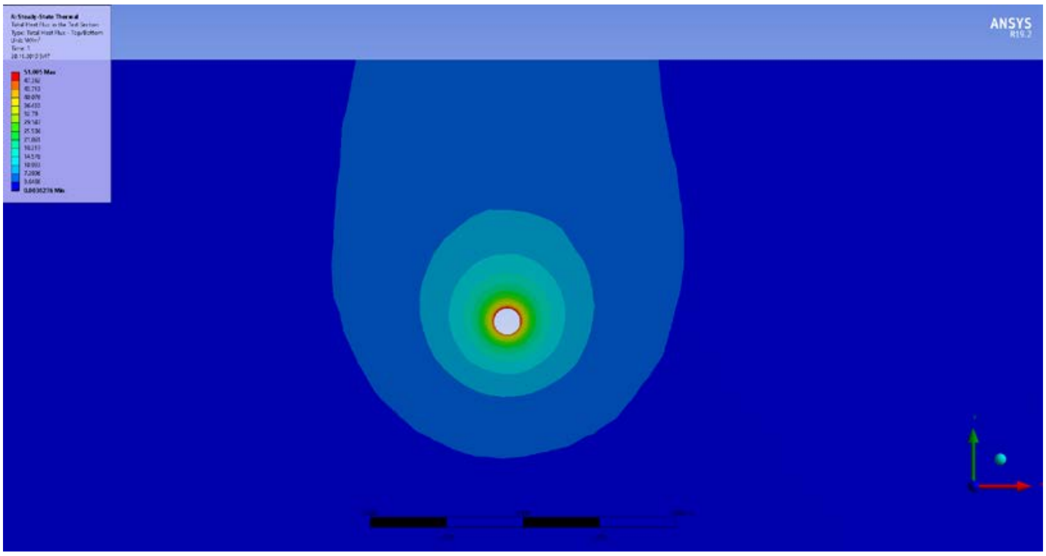


Fig.22 «Medium»

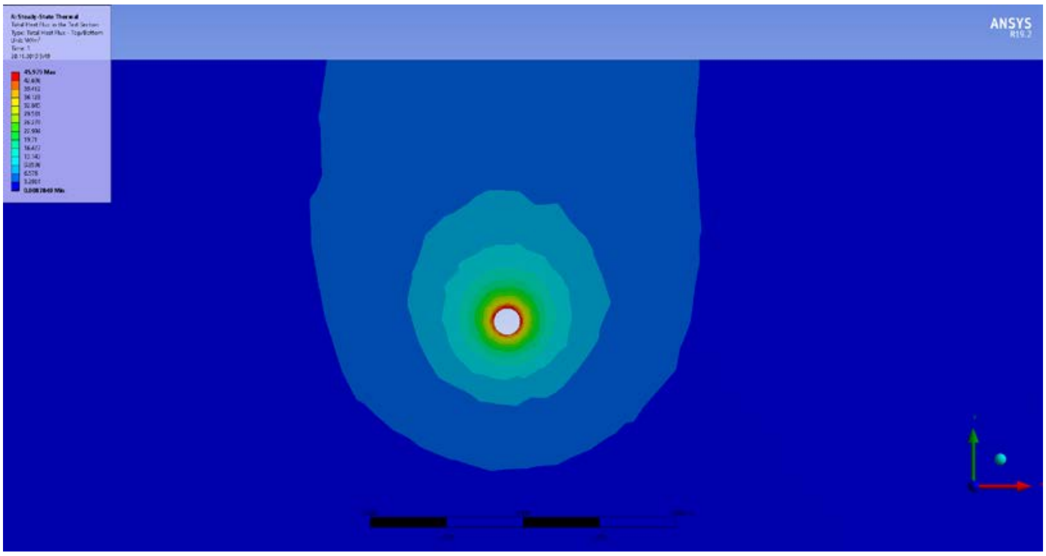


Fig.23 «Coarse»

«Fine» «Medium» «Coarse»

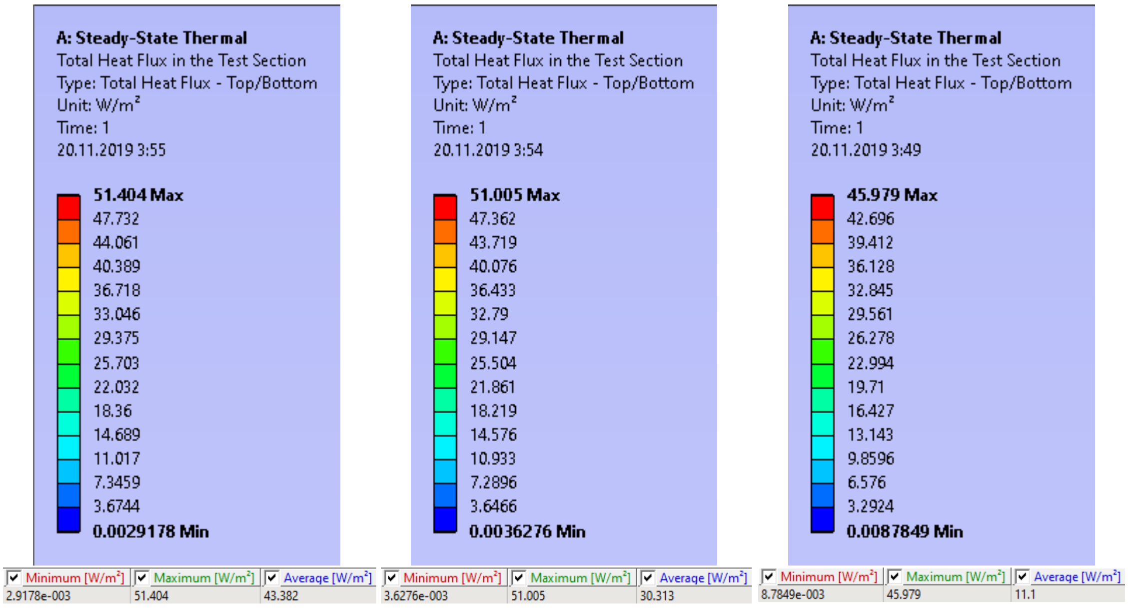



Fig.22 Total heat flux graphs

# Conclusion

Obtained data summary is presented in the tables below.

| Mesh | Maximum Total Heat Flux on the Pipe Surface | Maximum Temperature in the Test Section | Maximum Total Heat Flux in the Test Section |
|---|---|---|---|
| «Fine» | $51.404\ W/m^2$ | $80.0$ °C | $51.404\ W/m^2$ |
| «Medium» | $51.005\ W/m^2$ | $80.0$ °C | $51.005\ W/m^2$ |
| «Coarse» | $45.979\ W/m^2$ | $80.0$ °C | $45.979\ W/m^2$ |

Table 1: Maximum values

| Mesh | Minimum Total Heat Flux on the Pipe Surface | Minimum Temperature in the Test Section | Minimum Total Heat Flux in the Test Section |
|---|---|---|---|
| «Fine» | $46.311\ W/m^2$ | $-10.0$ °C | $2.9178 \cdot 10^{-3}\ W/m^2$ |
| «Medium» | $45.763\ W/m^2$ | $-10.0$ °C | $3.6276 \cdot 10^{-3}\ W/m^2$ |
| «Coarse» | $40.613\ W/m^2$ | $-10.0$ °C | $8.7849 \cdot 10^{-3}\ W/m^2$ |

Table 2: Minimum values

| Mesh | Average Total Heat Flux on the Pipe Surface | Average Temperature in the Test Section | Average Total Heat Flux in the Test Section |
|---|---|---|---|
| «Fine» | $\underline{48.802\ W/m^2}$ | $73.198$ °C | $43.382\ W/m^2$ |
| «Medium» | $48.324\ W/m^2$ | $57.535$ °C | $30.313\ W/m^2$ |
| «Coarse» | $43.509\ W/m^2$ | $29.711$ °C | $11.1\ W/m^2$ |

Table 3: Average values

| Mesh | Estimated Heat Loss of the Pipe ($Q = \dot{q}\pi DL$) | Error ($\frac{Estimated\ value}{True\ value} \cdot 100\%$) |
|---|---|---|
| «Fine» | $\underline{9198.96\ W}$ | $\underline{99.997\%}$ |
| «Medium» | 9108.86 | 99.017% |
| «Coarse» | 8201.25 | 89.151% |

Table 4: Estimation errors

| Mesh | Number of Nodes | Number of Elements | Total CPU Time |
|---|---|---|---|
| «Fine» | 18993 | 35215 | 1.750 $s$ |
| «Medium» | 3171 | 5969 | 0.656 $s$ |
| «Coarse» | 827 | 1569 | 0.562 $s$ |

Table 5: Solution details

As it is seen from the tables above, with the right choice of mesh, it is possible with to obtain a reliable data with a high confidence in a short time. The result of a given task was calculated with an **accuracy of 99.997%** in a **1.75 second**.

# Technical data

- **«Fine» computation**

Latency time from master to core 1 = 0.602 microseconds

Communication speed from master to core 1 = 9087.52 MB/sec

Total CPU time for main thread : 1.2 seconds
Total CPU time summed for all threads : 1.7 seconds

Elapsed time spent pre-processing model (/PREP7) : 0.1 seconds
Elapsed time spent solution - preprocessing : 0.2 seconds
Elapsed time spent computing solution : 0.6 seconds
Elapsed time spent solution - postprocessing : 0.0 seconds
Elapsed time spent post-processing model (/POST1) : 0.0 seconds

Equation solver used : Sparse (symmetric)

Maximum total memory used : 309.0 MB
Maximum total memory allocated : 3136.0 MB
Total physical memory available : 32 GB

- **«Medium» computation**

Latency time from master to core 1 = 0.607 microseconds

Communication speed from master to core 1 = 9011.77 MB/sec

Total CPU time for main thread : 0.6 seconds
Total CPU time summed for all threads : 0.6 seconds

Elapsed time spent pre-processing model (/PREP7) : 0.0 seconds
Elapsed time spent solution - preprocessing : 0.0 seconds
Elapsed time spent computing solution : 0.2 seconds
Elapsed time spent solution - postprocessing : 0.0 seconds
Elapsed time spent post-processing model (/POST1) : 0.0 seconds

Equation solver used : Sparse (symmetric)

Maximum total memory used : 91.0 MB
Maximum total memory allocated : 3136.0 MB
Total physical memory available : 32 GB

- **«Coarse» computation**

Latency time from master to core 1 = 0.599 microseconds

Communication speed from master to core 1 = 9211.03 MB/sec

Total CPU time for main thread : 0.6 seconds
Total CPU time summed for all threads : 0.5 seconds

Elapsed time spent pre-processing model (/PREP7) : 0.0 seconds
Elapsed time spent solution - preprocessing : 0.0 seconds
Elapsed time spent computing solution : 0.1 seconds
Elapsed time spent solution - postprocessing : 0.0 seconds
Elapsed time spent post-processing model (/POST1) : 0.0 seconds

Equation solver used : Sparse (symmetric)

Maximum total memory used : 87.0 MB
Maximum total memory allocated : 3136.0 MB
Total physical memory available : 32 GB

## Local machine specifications

| | |
|---|---|
| **Processor:** | Intel i9 9900k 5.0 GHz |
| **Video adapter:** | NVIDIA GEFORCE RTX 2080 Ti Founders Edition |
| **RAM:** | Corsair LPX 32GB (2x16GB) 3200 MHz |
| **Local storage:** | Samsung 970 EVO Plus Series 500 GB M2 SSD,<br>WD WD6003FZBX 7200 RPM 6 TB |

## Used programs

- ANSYS 19.2
- Autodesk Fusion 360
- CorelDraw 2019
- Adobe Photoshop CC 2019
- Paint

# References


- «Fundamentals of Heat and Mass Transfer» C.P. Kothandaraman
- https://labwrite.ncsu.edu/instructors/scientificart-parts.pdf
- https://grow.tecnico.ulisboa.pt/wp-content/uploads/2014/03/writing-in-english-a-practical-handbook-for-scientific-and-technical-writers-2000.pdf