STACKCALC

User's manual

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Indice

1. Introduction

This guide explains how to use StackCalc, a small program I wrote in my spare time, capable of calculating the chimney effect and estimate the dispersion of a gas in the atmosphere using the Pasquill-Gifford Gaussian model.

Currently, the program can calculate:

- Chimney effect due to natural draft, given an initial estimate of the chimney diameter and height, with automatic optimization of the minimum diameter and the tip diameter, if the latter is specified;
- Calculation of the thermal dispersion of the chimney;
- Calculation of the plume rise, given the atmospheric stability class according to the Pasquill classification;
- Calculation of the ground-level concentration profile, in the wind direction, of the main pollutants, using a Gaussian dispersion model.

The program's results can also be imported into other programs, such as Microsoft Excel, as StackCalc generates a text file that includes the concentration profile of various pollutants within a radius of up to 10 km from the emission point. The text file is preformatted with comma-separated values, making it easily importable into Microsoft Excel or other programs with similar import features. It can also directly create an xlsx file containing all the formatted calculations.

In Chapter 6 of this manual, you will find essential meteorology notes that are crucial for understanding the program's options and capabilities, which I recommend reading. It also contains useful information about the calculation models used.

It is emphasized once again that the program provides only a preliminary estimate and is not intended to replace a comprehensive analysis with dedicated tools.

1.1. Disclaimer

This software is provided "as-is," without any express or implied warranty. In no event shall the author be held liable for any damages arising from the use of this software.

Permission is granted to anyone to use this software and the data generated for any purpose, including commercial applications, and to redistribute it, provided that the origin of this software must not be misrepresented; you must not claim that you wrote the software..

2. Program Installation

If the program was not downloaded from www.melonimarco.it, I strongly recommend re-downloading it, as the version you are using may not be the latest.

The program requires Windows 7 or higher, Microsoft .NET 8.0 libraries, and a 64-bit processor to function. If the libraries are not already installed on the operating system, during the setup process, the program will automatically request permission to download them from the Microsoft website.

The minimum required resolution is 1366 x 768, while the recommended resolution is 1920 x 1080.

3. Main interface

Once the program is launched, the interface that appears is as follows:

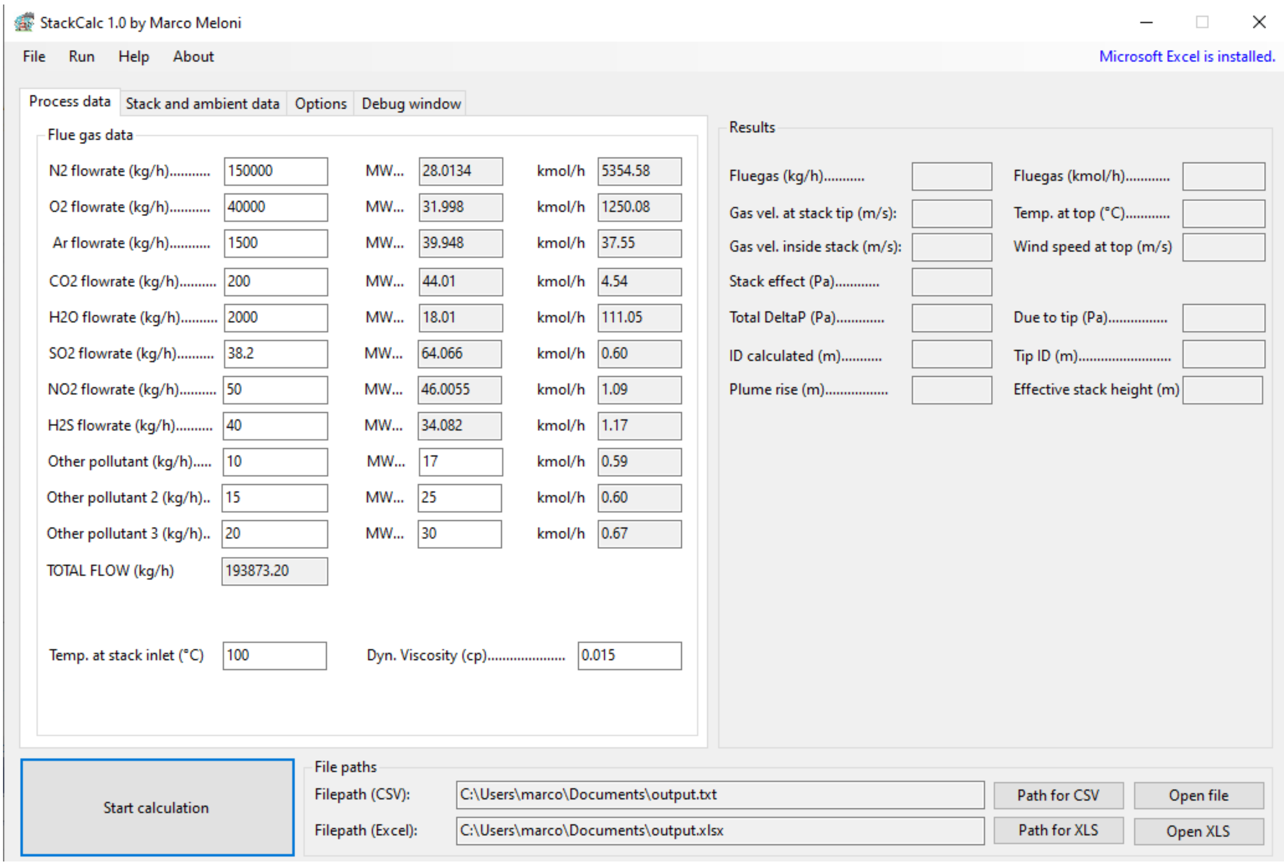


Figure 1: main interface of StackCalc (v.1.0)

The interface is divided into the following sections:

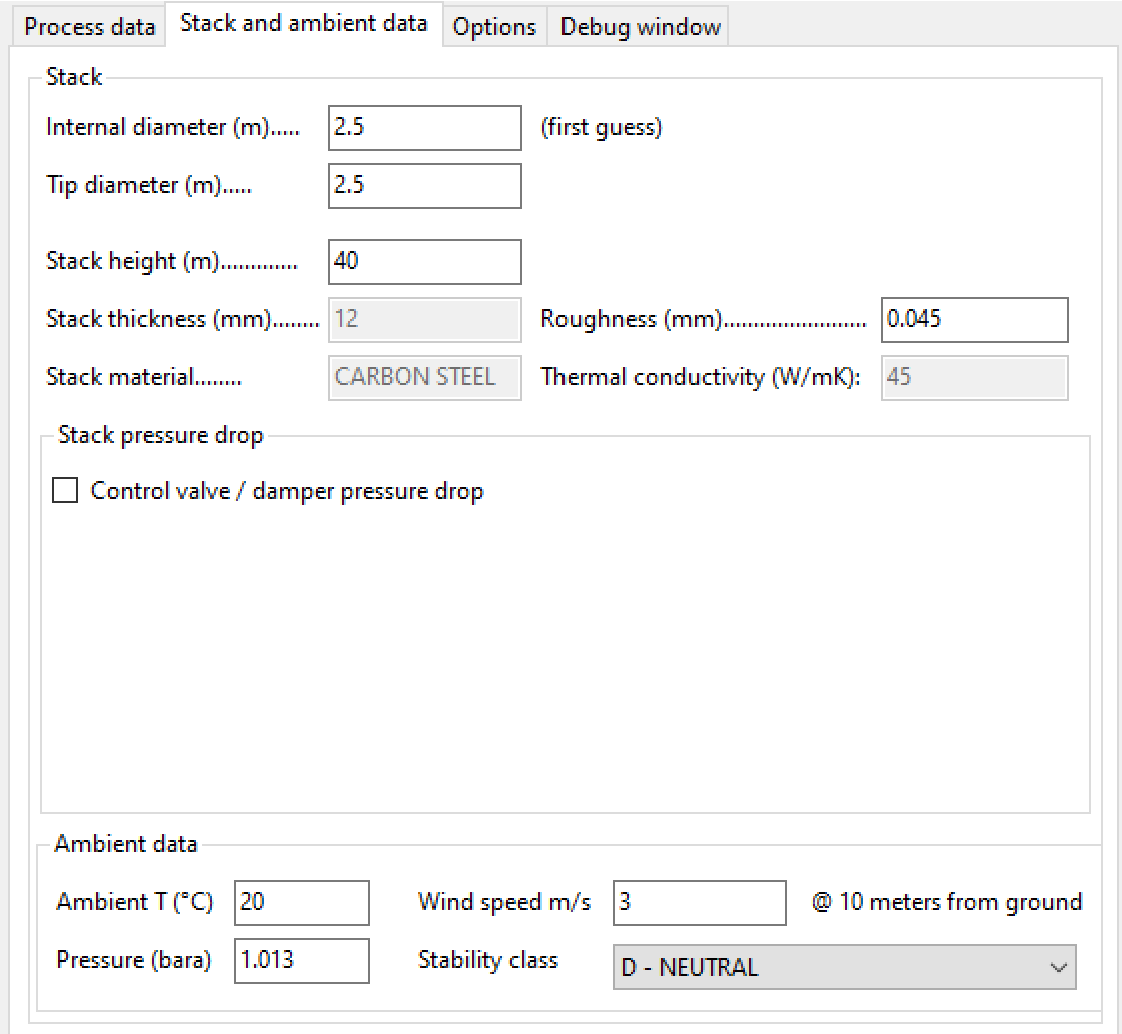
- **Process Data**: where you can enter the process data for the gas directed to the stack;
- **Stack and Ambient Data**: which allows you to enter the stack dimensions and environmental data;
- **Options**: which allows for the modification of certain calculation options;
- **Debug Window**: which contains a debug window where the program logs the calculation results;
- **File Paths**: to specify the save path for the CSV file containing the concentration profile calculated by the program;
- **Results**: where the program summarizes the calculated data.

3.1. Process data

The Process Data tab allows for the entry of flow rates for the components of the flue gas directed to the stack. The flow rates should be entered in kg/h, and the program automatically converts them to kmol/h.

You can also enter the flow rates for six pollutants. Three of these (SO_2, NO_2, H_2S) are already included by default. An additional three can be added if the molecular weight of the compound is known.

3.2. Stack and Ambient Data



In the “Stack Data” tab, you can currently enter the stack data: internal stack diameter, tip diameter, and stack height.

While the stack height is a fixed parameter that the program keeps constant during calculations, the internal diameter is only kept unchanged if the chimney effect is sufficient to overcome the pressure losses throughout the entire circuit. Otherwise, both the internal diameter and the tip diameter are incrementally increased by the program in 10 mm batches until the sizing criteria are met.

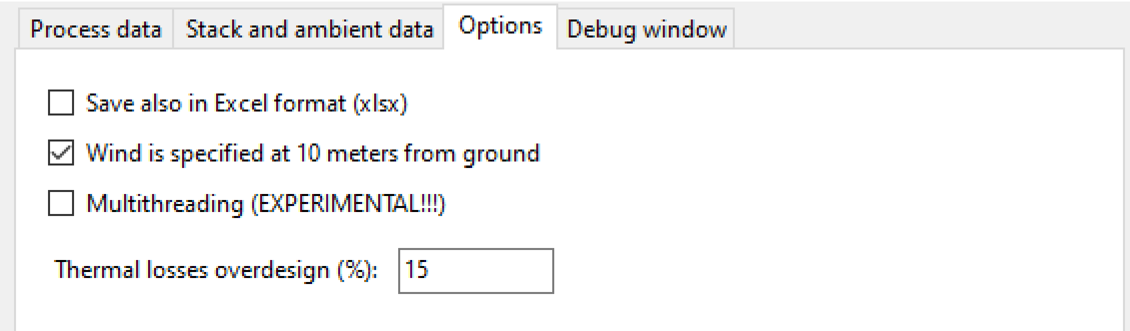
If you wish to simulate a stack without a tip, simply assign the same value to the tip diameter as the internal diameter. The restriction due to the tip is currently simulated as an orifice.

The "Control valve/damper pressure drop" option simulates the presence of a control valve or a damper during the calculation of the stack's pressure losses.

From this tab, you can also enter the environmental data: external air temperature, pressure, wind speed, and stability classes. By default, the wind speed is considered to be calculated at 10 meters above ground level; however, by adjusting the appropriate field in the “Options” tab, you can make that the calculation take into account the wind speed at the stack exit.

For a detailed description of the stability classes, please refer to the relevant chapter.

3.3. Options



The “Options” tab allows for the modification of certain parameters used in the calculation:

- **Save also in Excel format**: By enabling this option, you can save calculation results not only in text format but also in Excel's native format (xlsx).
- **Wind is specified at 10 meters from ground**: If the checkbox for this option is unchecked, the wind speed set in “Process Data” will be considered by the program as calculated at the stack exit point. If the checkbox remains checked, the wind speed at the stack exit will be calculated using the following formula:

$$u = u_{10} * \left(\frac{H}{10}\right)^{\propto}$$

Where:

u = wind speed at the stack exit point (m/s)

u_{10} = wind speed specified at 10 meters above ground (m/s)

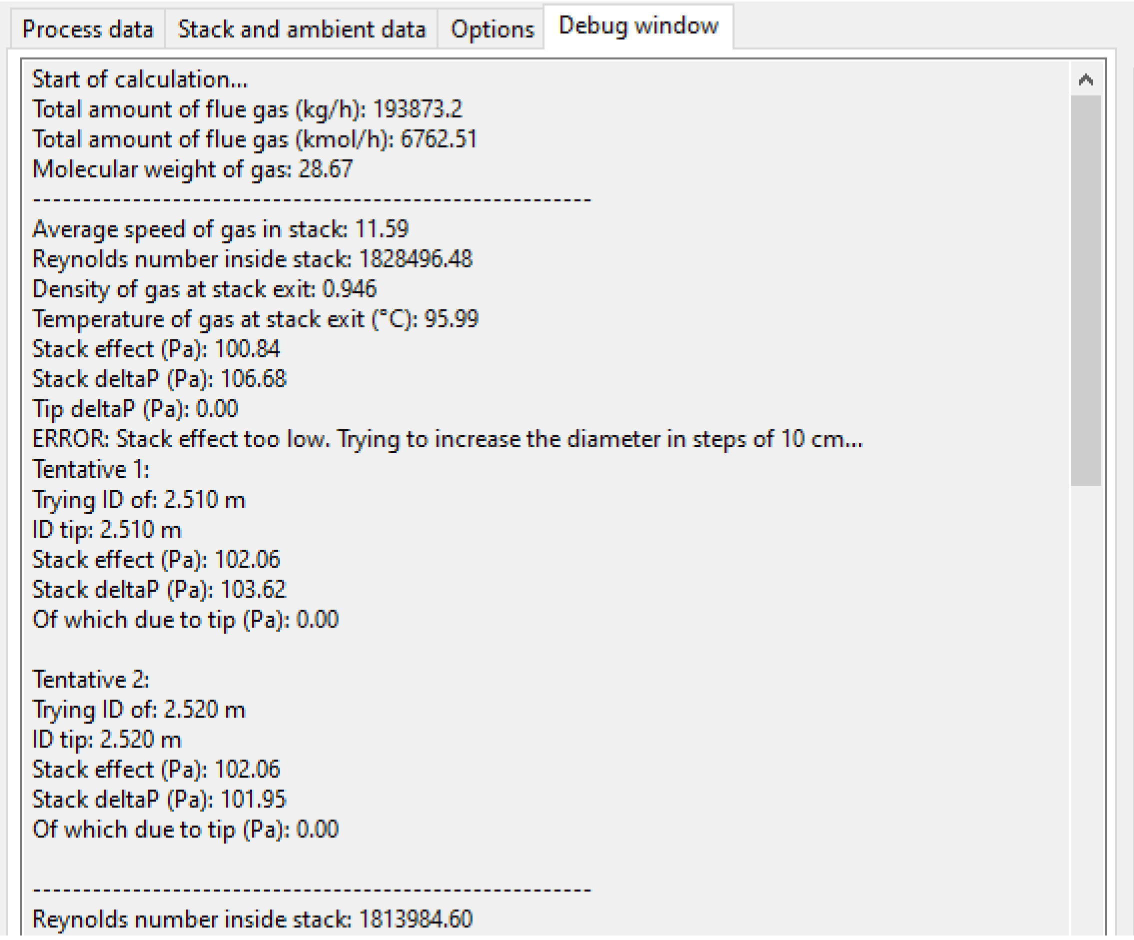
H = stack height (m)

$\propto$ = parameter dependent on the atmospheric stability class:

- 0.12 for class A (highly unstable)
- 0.16 for class B (moderately unstable)
- 0.2 for class C (slightly unstable)
- 0.25 for neutral class D
- 0.3 for class E (slightly stable)
- 0.4 for class F (stable)

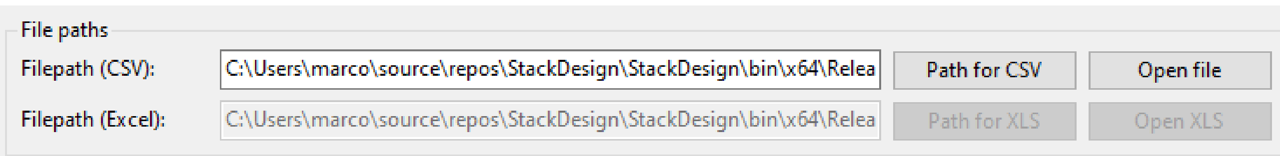
- **<u>Multithreading</u>**: Enables multi-core calculation. It is an experimental function that is not yet optimized.
- **<u>Thermal losses overdesign</u>**: Adds a safety margin to the thermal losses calculated by the program. This affects the calculation of the exit gas temperature.

3.4. Debug window



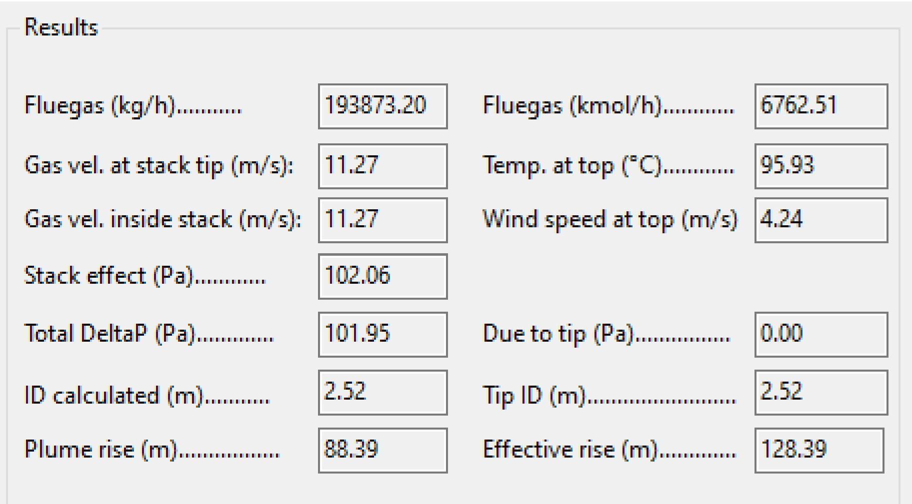
In the debug window, the program writes the results of the calculations or summarizes the most important ones.

3.5. File paths



In this tab, you can specify the path where the CSV file containing the pollutant dispersion data calculated by the program will be saved. Use the "Path for CSV" button to specify the save path and "Open file" to open the generated text file with Notepad.

3.6. Results



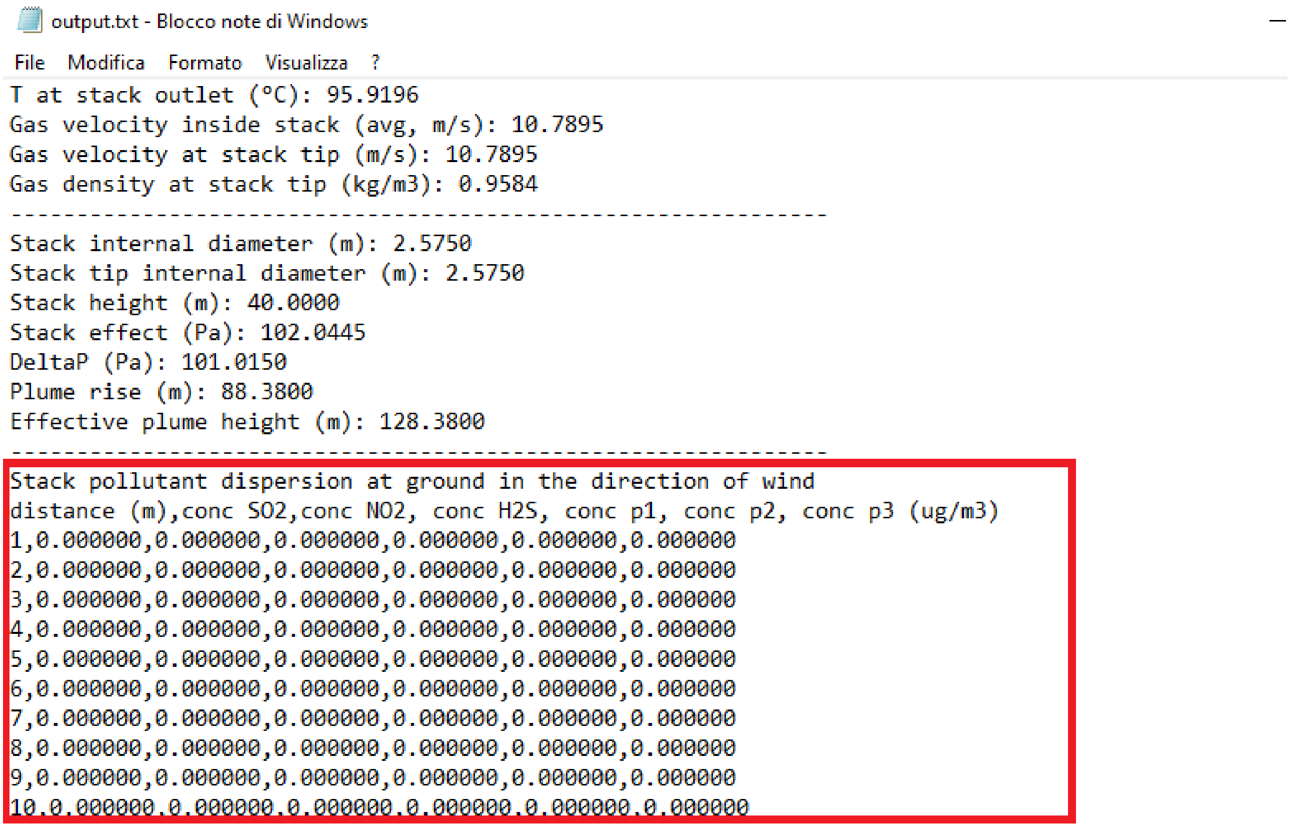
Once the program is configured, clicking the "Start Calculation" button will initiate the calculations. The results are displayed, as previously mentioned, both in the “Results” screen and in the text file specified in “File Paths”.

4. Importing Results into Microsoft Excel

Once the calculation is complete, the program saves the obtained concentration profile in a text file. The data can be imported into Excel in two ways:

- Importing the text file
- Saving the data directly in Excel format

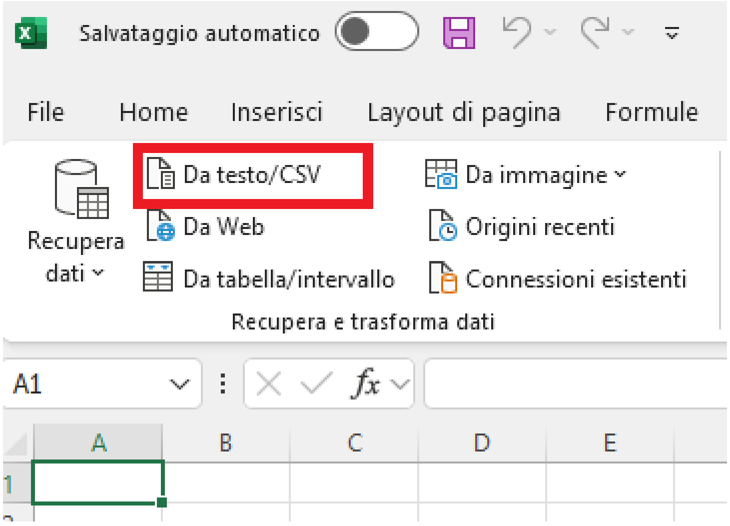
4.1. Importing the text file - first import method


output.txt - Blocco note di Windows

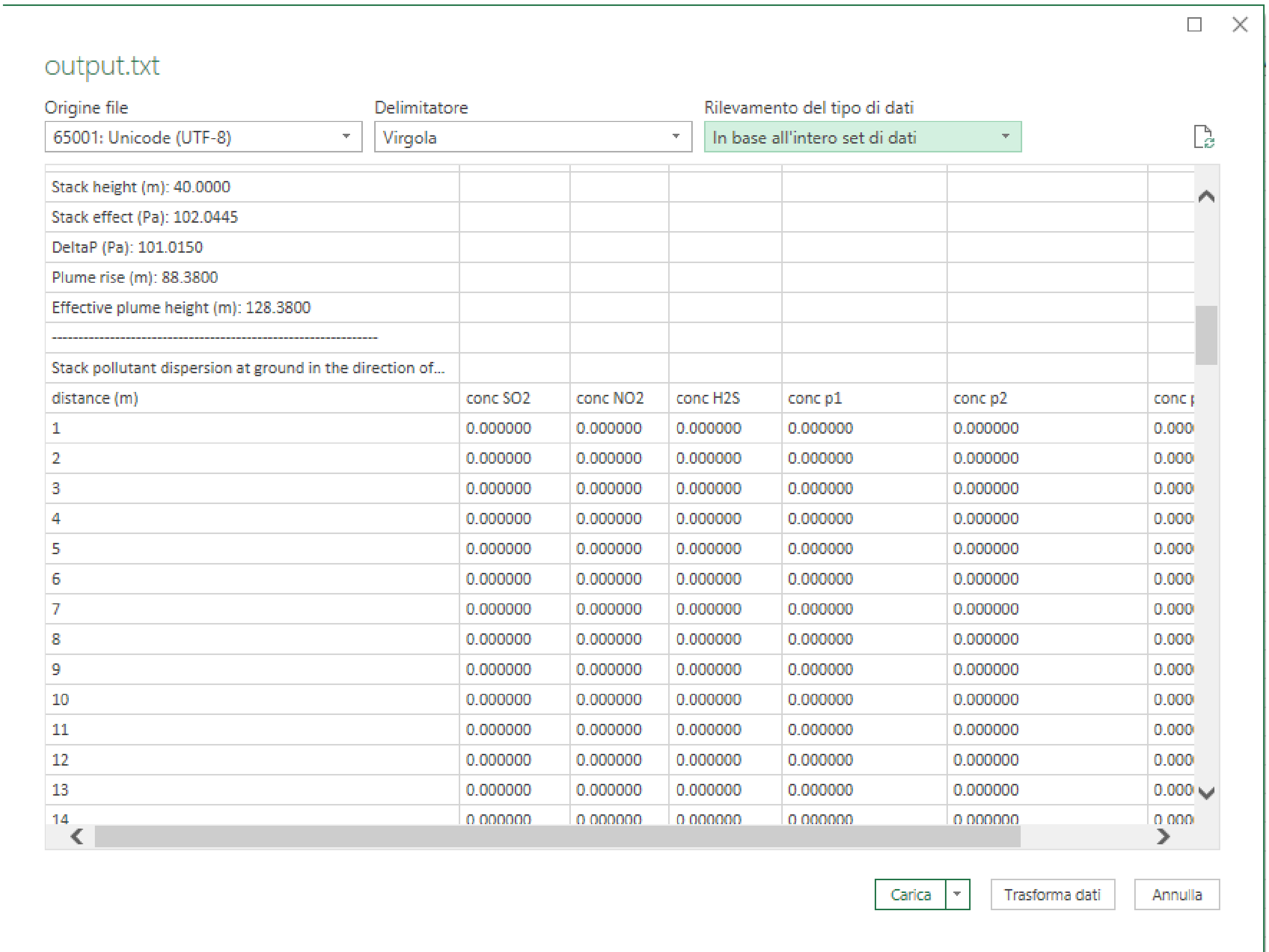
File Modifica Formato Visualizza ?

```
T at stack outlet (°C): 95.9196
Gas velocity inside stack (avg, m/s): 10.7895
Gas velocity at stack tip (m/s): 10.7895
Gas density at stack tip (kg/m3): 0.9584
--------------------------------------------------------------
Stack internal diameter (m): 2.5750
Stack tip internal diameter (m): 2.5750
Stack height (m): 40.0000
Stack effect (Pa): 102.0445
DeltaP (Pa): 101.0150
Plume rise (m): 88.3800
Effective plume height (m): 128.3800
--------------------------------------------------------------
Stack pollutant dispersion at ground in the direction of wind
distance (m),conc SO2,conc NO2, conc H2S, conc p1, conc p2, conc p3 (ug/m3)
1,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
2,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
3,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
4,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
5,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
6,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
7,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
8,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
9,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
10,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
```

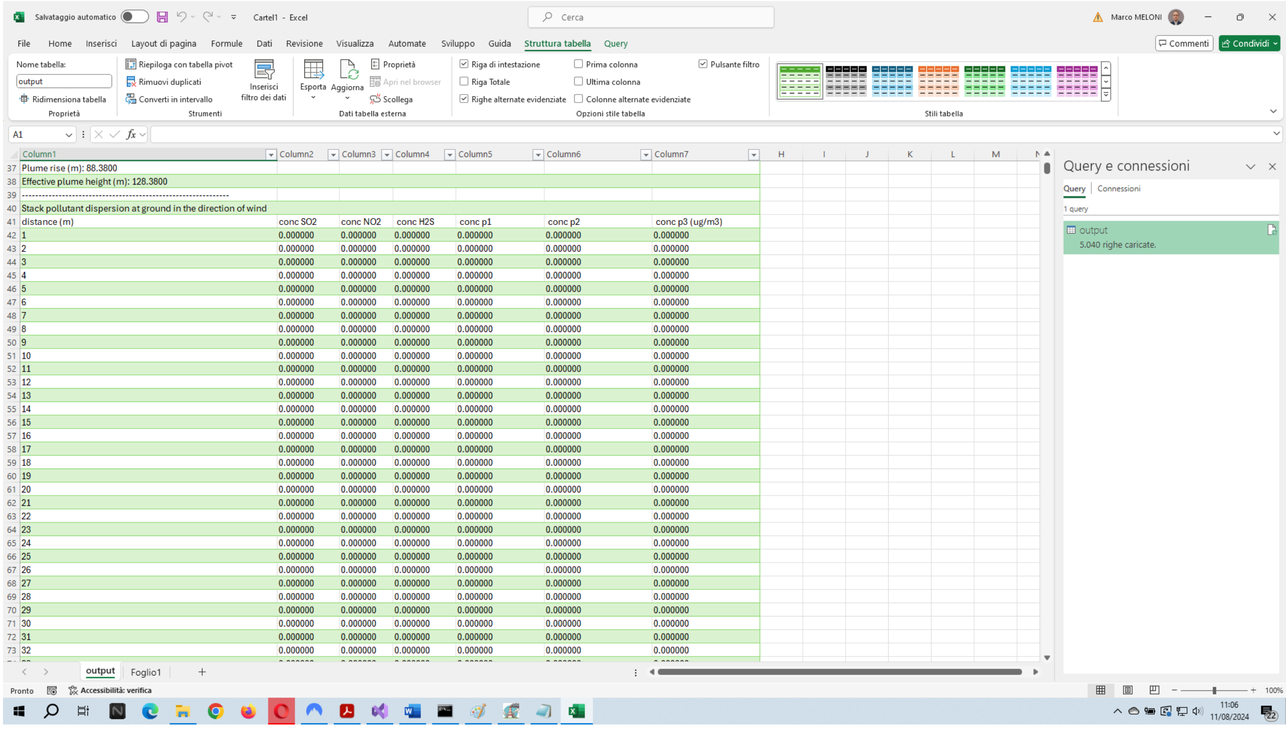
To import the file into Excel, the quickest method is to open a new Excel sheet and select the "Data -> From Text/CSV" menu:



Once you select the text file, Excel will analyze it. Select “Data Type Detection” and choose “Based on the entire dataset” to allow Excel to correctly recognize the file:



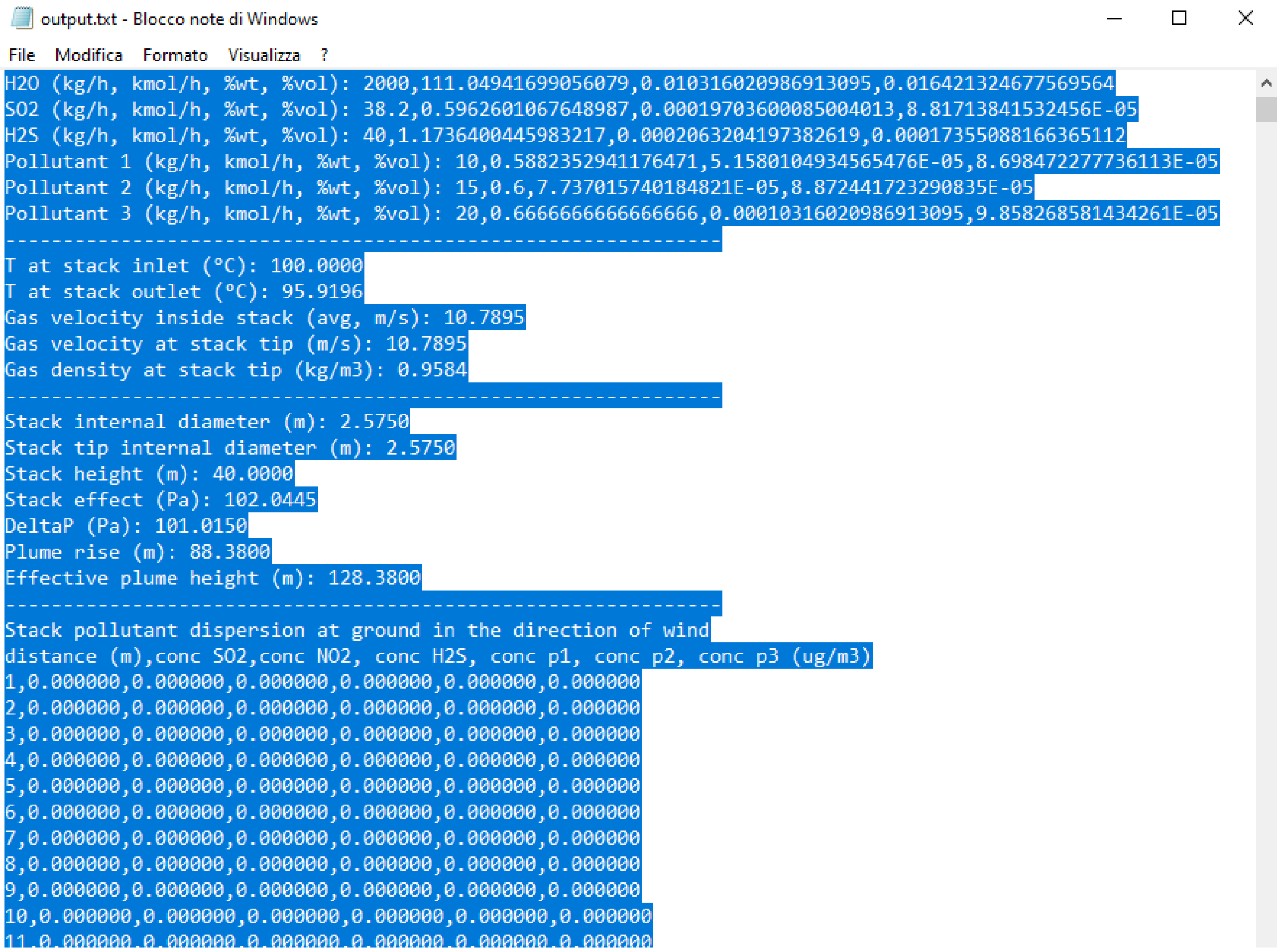
Finally, click the “Load” button to load the data into an Excel sheet:



4.2. Alternative Import Method

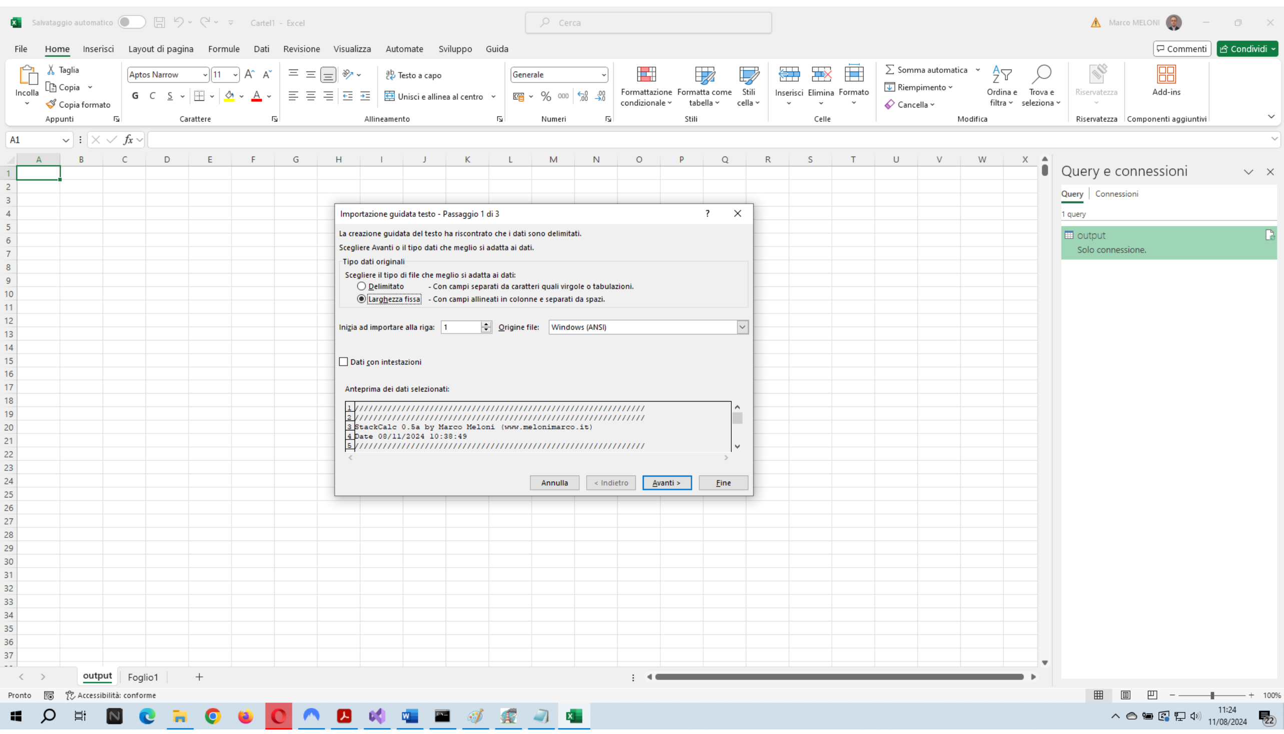
Alternatively, if Excel does not correctly recognize the ranges (which unfortunately happens often with recent versions), you can proceed in an even simpler way:

1. Open the output file and select all the data it contains, then copy it to the clipboard (CTRL+A, followed by CTRL+C):

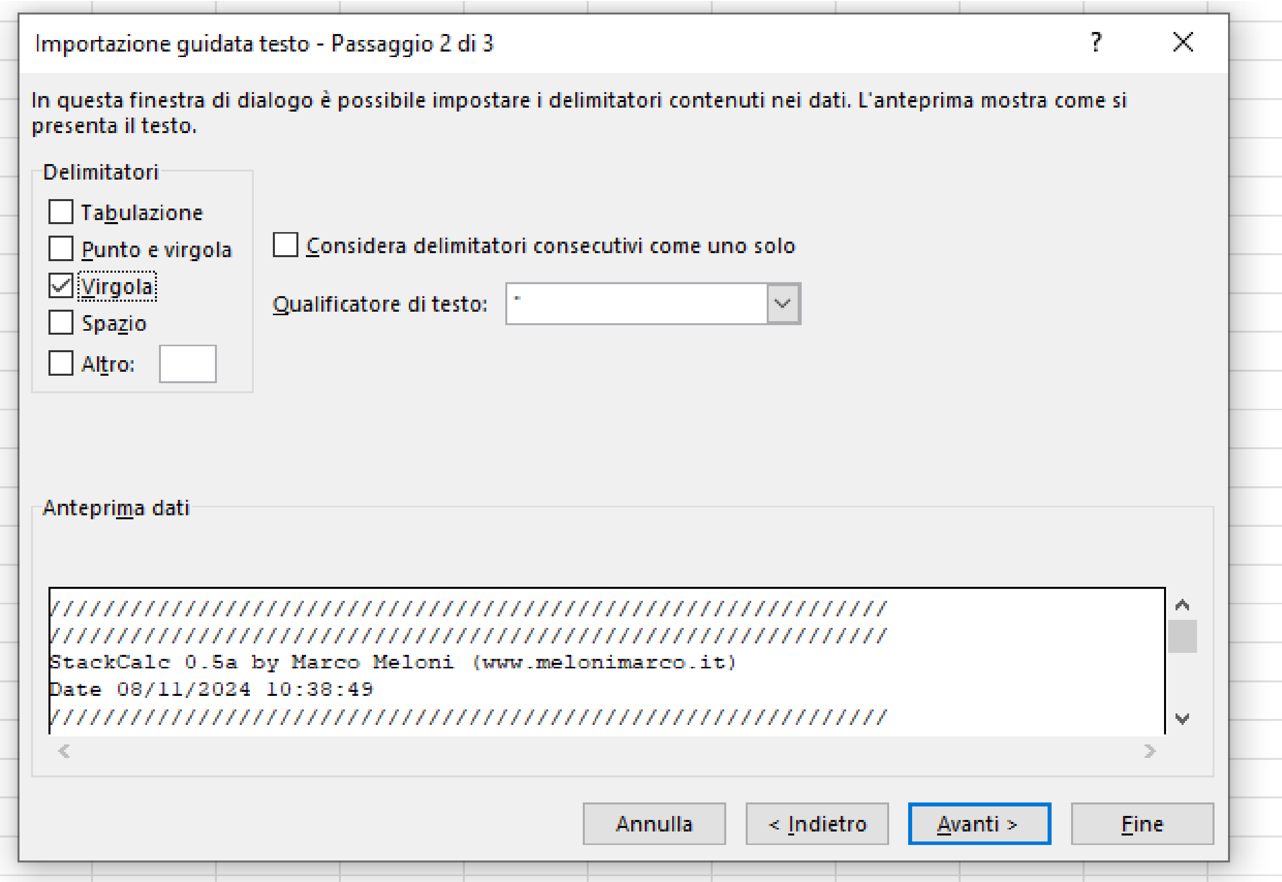


```
output.txt - Blocco note di Windows
File  Modifica  Formato  Visualizza  ?
H2O (kg/h, kmol/h, %wt, %vol): 2000,111.04941699056079,0.010316020986913095,0.016421324677569564
SO2 (kg/h, kmol/h, %wt, %vol): 38.2,0.5962601067648987,0.00019703600085004013,8.81713841532456E-05
H2S (kg/h, kmol/h, %wt, %vol): 40,1.1736400445983217,0.0002063204197382619,0.00017355088166365112
Pollutant 1 (kg/h, kmol/h, %wt, %vol): 10,0.5882352941176471,5.1580104934565476E-05,8.698472277736113E-05
Pollutant 2 (kg/h, kmol/h, %wt, %vol): 15,0.6,7.737015740184821E-05,8.872441723290835E-05
Pollutant 3 (kg/h, kmol/h, %wt, %vol): 20,0.6666666666666666,0.00010316020986913095,9.858268581434261E-05
--------------------------------------------------------------
T at stack inlet (°C): 100.0000
T at stack outlet (°C): 95.9196
Gas velocity inside stack (avg, m/s): 10.7895
Gas velocity at stack tip (m/s): 10.7895
Gas density at stack tip (kg/m3): 0.9584
--------------------------------------------------------------
Stack internal diameter (m): 2.5750
Stack tip internal diameter (m): 2.5750
Stack height (m): 40.0000
Stack effect (Pa): 102.0445
DeltaP (Pa): 101.0150
Plume rise (m): 88.3800
Effective plume height (m): 128.3800
--------------------------------------------------------------
Stack pollutant dispersion at ground in the direction of wind
distance (m),conc SO2,conc NO2, conc H2S, conc p1, conc p2, conc p3 (ug/m3)
1,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
2,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
3,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
4,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
5,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
6,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
7,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
8,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
9,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
10,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
11,0.000000,0.000000,0.000000,0.000000,0.000000,0.000000
```

2. Open a new Excel sheet and select "Home > Paste > Text Import Wizard". The following window will appear:



3. Select "Delimited," and in the next screen choose "Comma" and click "Next":



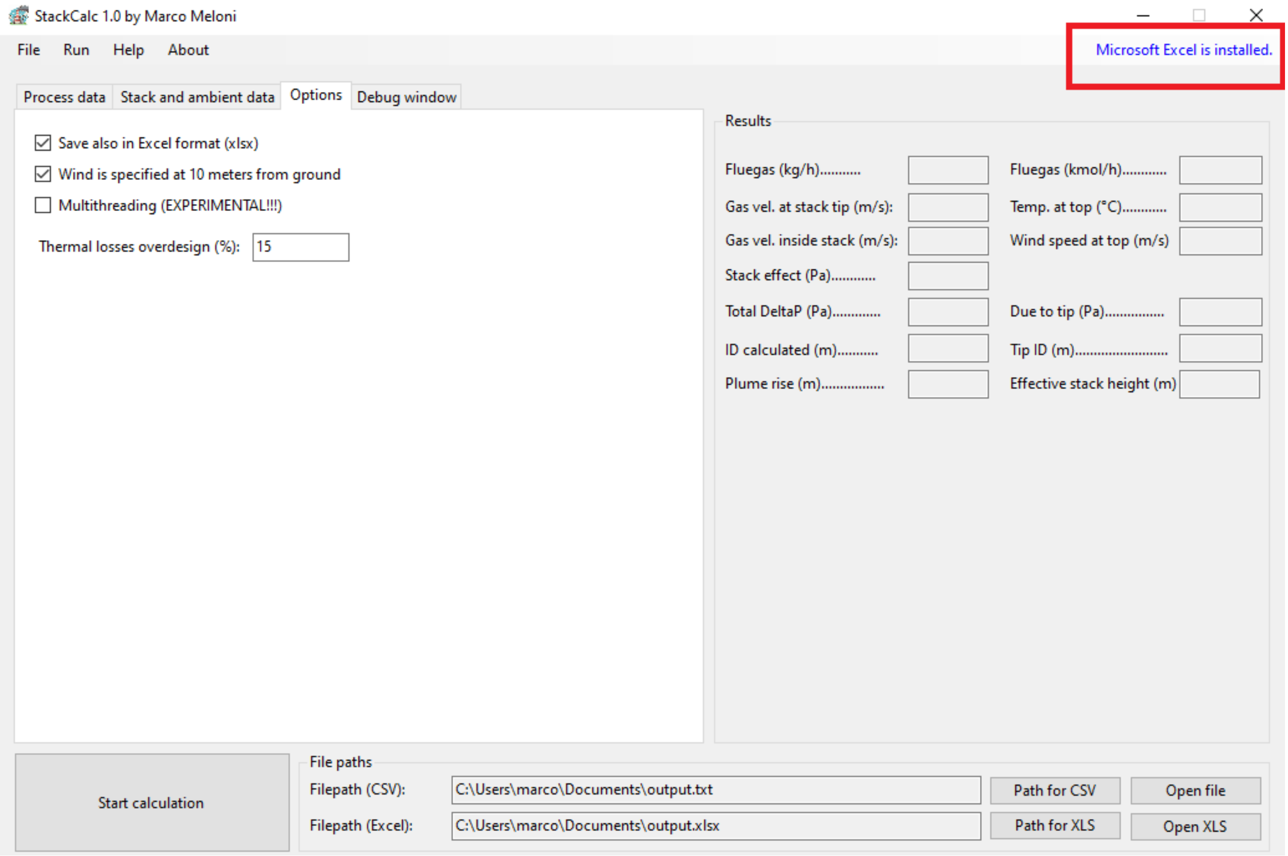
4. Finally, click “Finish” to have the data perfectly arranged:

38	---						
39	Stack pollutant dispersion at ground in the direction of wind						
40	distance (	conc SO2	conc NO2	conc H2S	conc p1	conc p2	conc p3 (ug/m3)
41	1	0	0	0	0	0	0
42	2	0	0	0	0	0	0
43	3	0	0	0	0	0	0
44	4	0	0	0	0	0	0
45	5	0	0	0	0	0	0
46	6	0	0	0	0	0	0
47	7	0	0	0	0	0	0
48	8	0	0	0	0	0	0
49	9	0	0	0	0	0	0
50	10	0	0	0	0	0	0
51	11	0	0	0	0	0	0
52	12	0	0	0	0	0	0
53	13	0	0	0	0	0	0
54	14	0	0	0	0	0	0
55	15	0	0	0	0	0	0
56	16	0	0	0	0	0	0
57	17	0	0	0	0	0	0
58	18	0	0	0	0	0	0
59	19	0	0	0	0	0	0
60	20	0	0	0	0	0	0
61	21	0	0	0	0	0	0
62	22	0	0	0	0	0	0
63	23	0	0	0	0	0	0
64	24	0	0	0	0	0	0
65	25	0	0	0	0	0	0

4.3. Save Results in Native Microsoft Excel Format

Starting from version 1.0 of the program, StackCalc is now capable of directly creating a native .xlsx file in which all the results calculated by the program are saved. However, for this to be possible, a version of Microsoft Excel must be installed on the PC.

StackCalc automatically checks at startup whether a version of Microsoft Excel is installed on the PC, and if it is, this is indicated in the top-right corner of the main window:

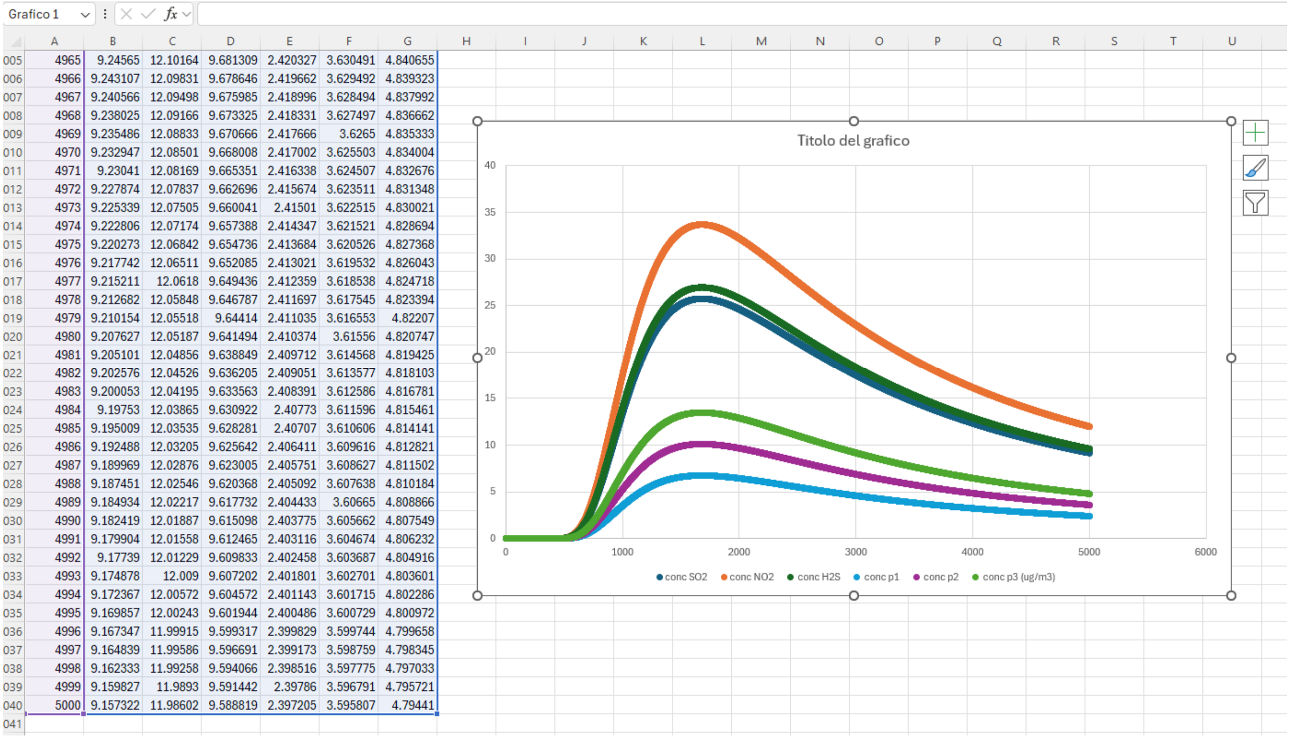


If Microsoft Excel is installed, to save the results in XLSX format, simply check the box "Save also in Excel format (xlsx)" located in the "Options" menu, select the file save path by clicking the "Path for XLSX" button, and start the calculation.

Note: Saving in Excel format takes longer than saving in text format. A few extra seconds of waiting is normal.

4.4. Plotting the Results

Once the data is imported, you can immediately display the pollutant concentration graph by selecting the entire range of interest and choosing one of the scatter plot options:



	A	B	C	D	E	F	G
005	4965	9.24565	12.10164	9.681309	2.420327	3.630491	4.840655
006	4966	9.243107	12.09831	9.678646	2.419662	3.629492	4.839323
007	4967	9.240566	12.09498	9.675985	2.418996	3.628494	4.837992
008	4968	9.238025	12.09166	9.673325	2.418331	3.627497	4.836662
009	4969	9.235486	12.08833	9.670666	2.417666	3.6265	4.835333
010	4970	9.232947	12.08501	9.668008	2.417002	3.625503	4.834004
011	4971	9.23041	12.08169	9.665351	2.416338	3.624507	4.832676
012	4972	9.227874	12.07837	9.662696	2.415674	3.623511	4.831348
013	4973	9.225339	12.07505	9.660041	2.41501	3.622515	4.830021
014	4974	9.222806	12.07174	9.657388	2.414347	3.621521	4.828694
015	4975	9.220273	12.06842	9.654736	2.413684	3.620526	4.827368
016	4976	9.217742	12.06511	9.652085	2.413021	3.619532	4.826043
017	4977	9.215211	12.0618	9.649436	2.412359	3.618538	4.824718
018	4978	9.212682	12.05848	9.646787	2.411697	3.617545	4.823394
019	4979	9.210154	12.05518	9.64414	2.411035	3.616553	4.82207
020	4980	9.207627	12.05187	9.641494	2.410374	3.61556	4.820747
021	4981	9.205101	12.04856	9.638849	2.409712	3.614568	4.819425
022	4982	9.202576	12.04526	9.636205	2.409051	3.613577	4.818103
023	4983	9.200053	12.04195	9.633563	2.408391	3.612586	4.816781
024	4984	9.19753	12.03865	9.630922	2.40773	3.611596	4.815461
025	4985	9.195009	12.03535	9.628281	2.40707	3.610606	4.814141
026	4986	9.192488	12.03205	9.625642	2.406411	3.609616	4.812821
027	4987	9.189969	12.02876	9.623005	2.405751	3.608627	4.811502
028	4988	9.187451	12.02546	9.620368	2.405092	3.607638	4.810184
029	4989	9.184934	12.02217	9.617732	2.404433	3.60665	4.808866
030	4990	9.182419	12.01887	9.615098	2.403775	3.605662	4.807549
031	4991	9.179904	12.01558	9.612465	2.403116	3.604674	4.806232
032	4992	9.17739	12.01229	9.609833	2.402458	3.603687	4.804916
033	4993	9.174878	12.009	9.607202	2.401801	3.602701	4.803601
034	4994	9.172367	12.00572	9.604572	2.401143	3.601715	4.802286
035	4995	9.169857	12.00243	9.601944	2.400486	3.600729	4.800972
036	4996	9.167347	11.99915	9.599317	2.399829	3.599744	4.799658
037	4997	9.164839	11.99586	9.596691	2.399173	3.598759	4.798345
038	4998	9.162333	11.99258	9.594066	2.398516	3.597775	4.797033
039	4999	9.159827	11.9893	9.591442	2.39786	3.596791	4.795721
040	5000	9.157322	11.98602	9.588819	2.397205	3.595807	4.79441
041							

Figure 2: Distribution of major pollutants at ground level, based on distance from the emission point

Concentration values are expressed in µg/m³, and distance is expressed in meters.

5. Calculating the Chimney Effect – Model Used

The chimney effect is a physical phenomenon related to the movement of air or other fluids within a vertical conduit, such as a chimney or a tower. It is based on the expansion of gases caused by their heating and the resulting establishment of a difference in density and pressure between the lowest point (where the gas is heated) and the highest point (where the gas exits to the outside).

The chimney effect is influenced by various parameters, including the height of the conduit and the temperature difference between the base and the top. The height of the chimney is particularly significant: the greater the height, the more pronounced the pressure gradient that develops, and thus the stronger the upward air current. The temperature difference is another crucial factor: the larger the difference between the internal and external temperatures, the more marked the density variation and, consequently, the more intense the airflow.

For the chimney to generate sufficient draft, it must be capable of overcoming all the pressure losses encountered along the path to the top of the chimney.

StackCalc models this phenomenon using the following equation:

$$H_S g(\rho_a - \rho_f) = \sum \Delta P_C + \sum \Delta P_D + \Delta P_{TIP} \tag{5.1}$$

Where

- H_s is the height of the chimney, in meters;
- g is the acceleration due to gravity, in m/s²
- $\rho_a - \rho_f$ is the difference between the densities of the external air and the gas flowing inside the chimney (kg/m³). The density for both fluids is calculated using the ideal gas law.
- $\sum \Delta P_C$ is the sum of all concentrated pressure losses along the considered section of the circuit (Pa). The losses considered by the program currently include:
  - Stack inlet
  - Stack outlet
  - resence or absence of a control valve or damper
- $\sum \Delta P_D$ is the sum of the distributed pressure losses along the considered section of the circuit (Pa). These are calculated using the Darcy-Weisbach equation, with the Darcy factor computed through the Colebrook-White formula. For a detailed description, refer to fluid dynamics texts.
- Finally, ΔP_{TIP} is the pressure loss present if a tip diameter smaller than the chimney diameter is specified. The program simulates this restriction by approximating the tip as a concentric orifice. The program automatically limits the tip diameter to a minimum value of 70% of the stack diameter if the input value is below this limit.

If the natural draft is insufficient, the program iterates by progressively increasing the diameter of the stack and the tip (if present) until the two values converge.

6. Meteorology and Models Used

Meteorology is the science that studies the Earth's atmosphere and the phenomena occurring within it. It analyzes atmospheric conditions such as temperature, humidity, pressure, wind, precipitation, and other factors that influence climate and weather.

The dispersion of gaseous emissions from a chimney falls within the realm of meteorology. This phenomenon depends on a series of factors that affect the behavior of pollutants once they are released into the atmosphere:

Type of Emissions: The physical and chemical properties of the emitted gases, such as density, chemical reactivity, and water solubility, determine how they disperse and deposit in the environment.

Meteorological Conditions: Wind, temperature, humidity, and atmospheric stability are key determinants. Wind can transport emissions over long distances, while temperature and humidity influence density and dispersion speed.

Atmospheric Stability: The stability of the atmosphere determines the air's ability to mix vertically. In stable atmospheric conditions, vertical dispersion is limited, leading to higher concentrations of pollutants near the source. In unstable conditions, gases tend to disperse more rapidly in the vertical direction.

Chimney Height: The height of the chimney affects the distance traveled by the emissions before falling to the ground. Taller chimneys tend to disperse pollutants over a larger area, reducing local concentrations but increasing potential impacts on more distant areas.

Topography: The topography of the location also influences the dispersion of emissions. The presence of large bodies of water (lakes, seas) and buildings significantly impacts how pollutants distribute in the environment.

6.1. Meteorological Conditions: Temperature

When considering a small volume of gas exiting from the chimney, it enters the atmosphere with its own temperature, different from the atmospheric temperature, and its own volume. It will generally undergo cooling and expansion.

The conditions of the gas exiting the chimney, as well as its physical and chemical properties, and the characteristics of the surrounding atmospheric air, determine whether the gas will experience positive, neutral, or negative buoyancy.

It is evident that buoyancy depends on the difference between the density of the gas and that of the surrounding air, and ultimately, when considering both as ideal gases, on their molecular weights and temperatures.

The molecular weight of the gas can be approximated as constant over time, as we are not considering chemical reactions, but this is not the case for the gas temperature, which may vary due to dilution with the surrounding air or due to evaporation or condensation phenomena originating from the release.

Regarding pressure, like temperature, it will vary with altitude.

If z represents the altitude of the gas volume relative to the ground, the following equation expresses the variation of air pressure with altitude:

$$dP = -\rho * g * dZ \quad (6.1)$$

Applying the ideal gas law and considering an isentropic transformation law for temperature:

$$T = T_1 * \left(\frac{P}{P_1}\right)^{\frac{K-1}{K}} \quad (6.2)$$

Where

- T and T1 are the temperatures under the given pressure conditions (K)
- P and P1 are the pressures at the measurement points (Pa)
- K is the isentropic transformation coefficient (1.4 for air)

By integrating equation 6.1 and substituting in the result from equation 6.2, it can be shown that under adiabatic conditions, the temperature variation with altitude follows the relation:

$$\frac{dT}{dZ} = -\frac{(k-1)*g}{k*R*PM} \quad (6.3)$$

Where

- g is the gravitational acceleration constant;
- R is the ideal gas constant;
- PM is the molecular weight of air.

This equation allows us to immediately determine that under adiabatic conditions, there is a decrease of approximately 0.01°C in temperature for every meter of altitude gain. Under these conditions, the small volume of gas will be in equilibrium with the surrounding air at each altitude, meaning it will not be forced to rise or fall, thus remaining in neutral conditions. This situation is typical when the sky is overcast, cloudy, and with moderate to strong winds.

However, there can be other air conditions that result in entirely different buoyancy conditions for the gas.

In sub-adiabatic conditions (-0.01°C/m < dT/dZ < 0°C/m), the rate of temperature decrease is greater than the adiabatic rate. In this case, a small volume of gas at altitude Z_2 would have a temperature lower than that of the surrounding atmosphere at the same altitude.

The gas would therefore be heavier than the surrounding air and would tend to descend until reaching an equilibrium altitude Z_{eq}.

Conversely, if the gas is at an altitude lower than Z_{eq}, since the temperature of the air at this point is lower than that of the gas, the gas will tend to rise until it reaches the equilibrium point at Z_{eq}. This condition is described as stable.

A special case of stability occurs when $\frac{dT}{dZ} = 0\ °C/m$ (isothermy), in which case the atmosphere is very stable.

In super-adiabatic conditions ($\frac{dT}{dZ} < -0.01\ °C/m$), the previously described phenomenon is reversed: a small volume of gas at altitude Z_2, being lighter than the air, will continue to rise, while at a point Z_1 below the intersection with the adiabatic curve, the gas, being heavier, will continue to descend. In these cases, the atmosphere is described as unstable.

These conditions are typical in cases of strong irradiation or when cold air passes over warm ground.

Finally, there can be cases where $\frac{dT}{dZ} > 0$. These are referred to as thermal inversions. A typical example is the transition from day to night.

The following graphs illustrate the concepts expressed above:

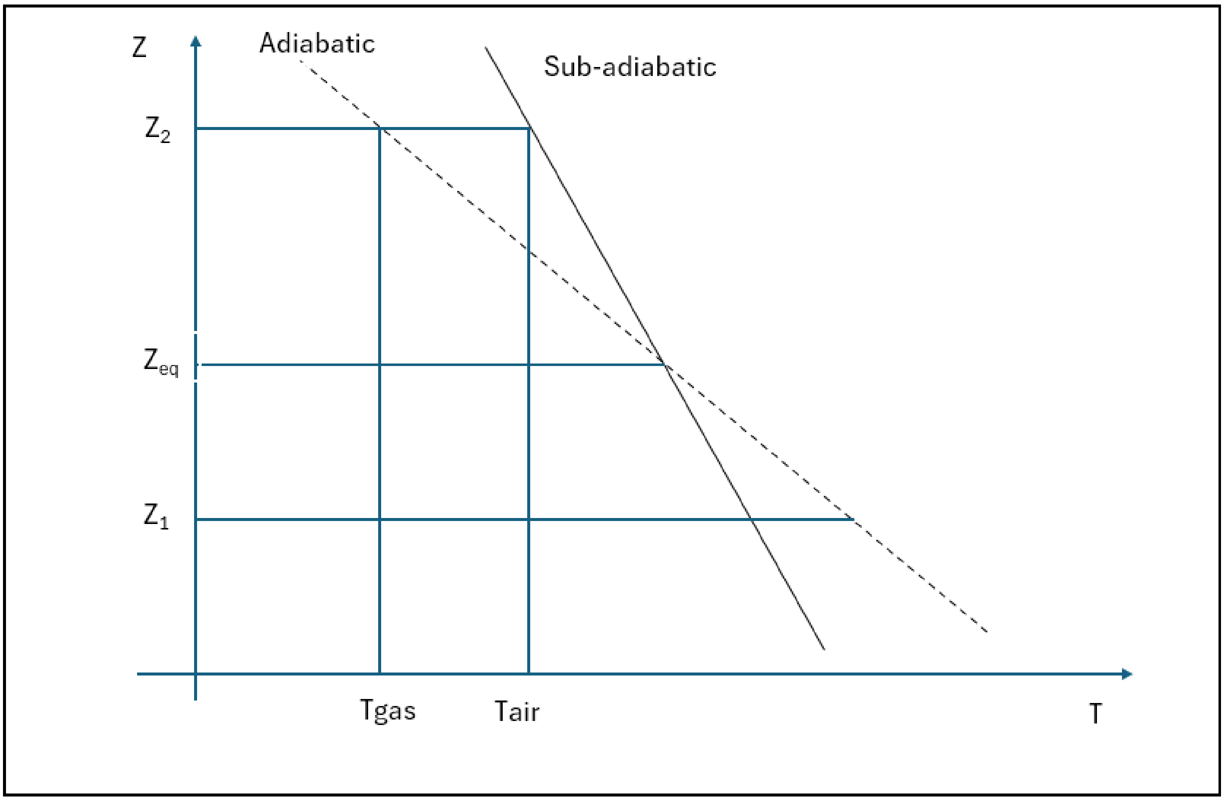


Figura 3: Sub-adiabatic Cooling Condition

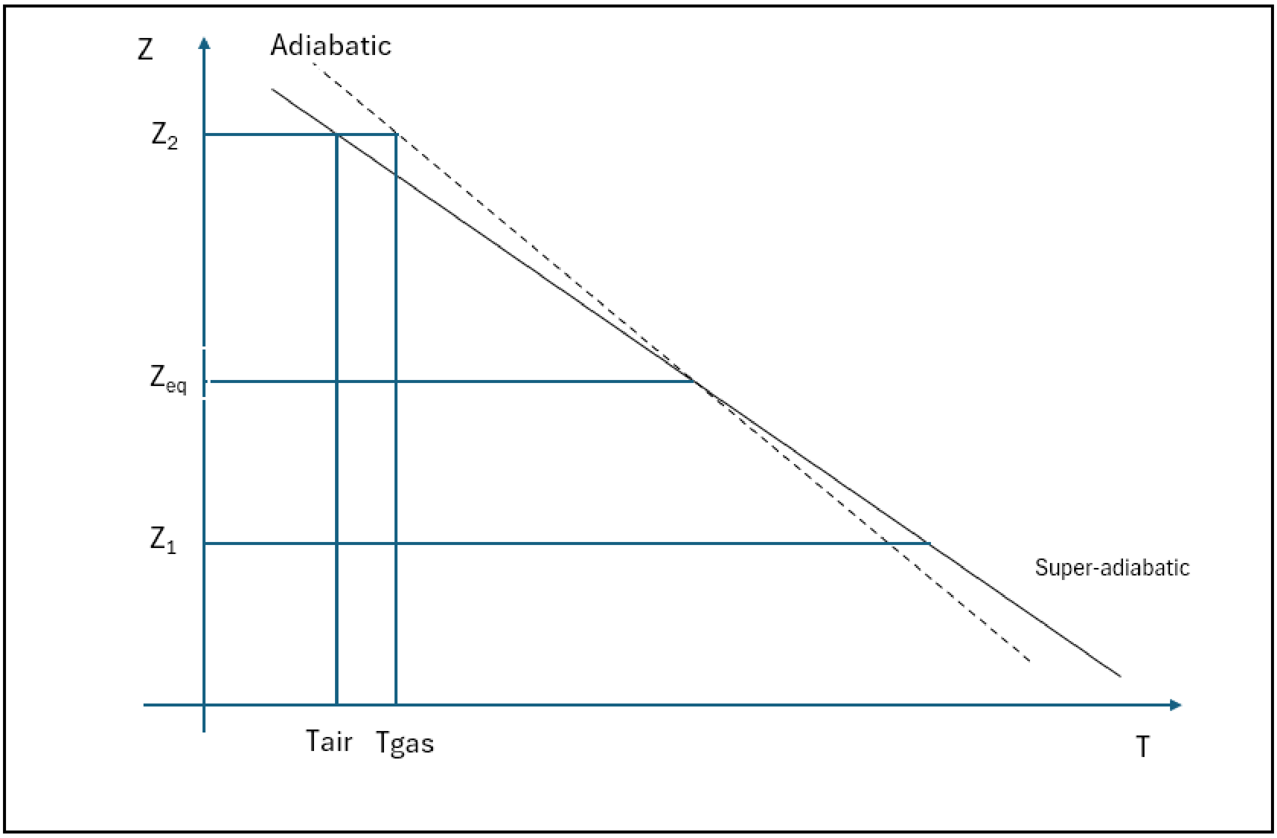


Figura 4: Super-Adiabatic Cooling Condition

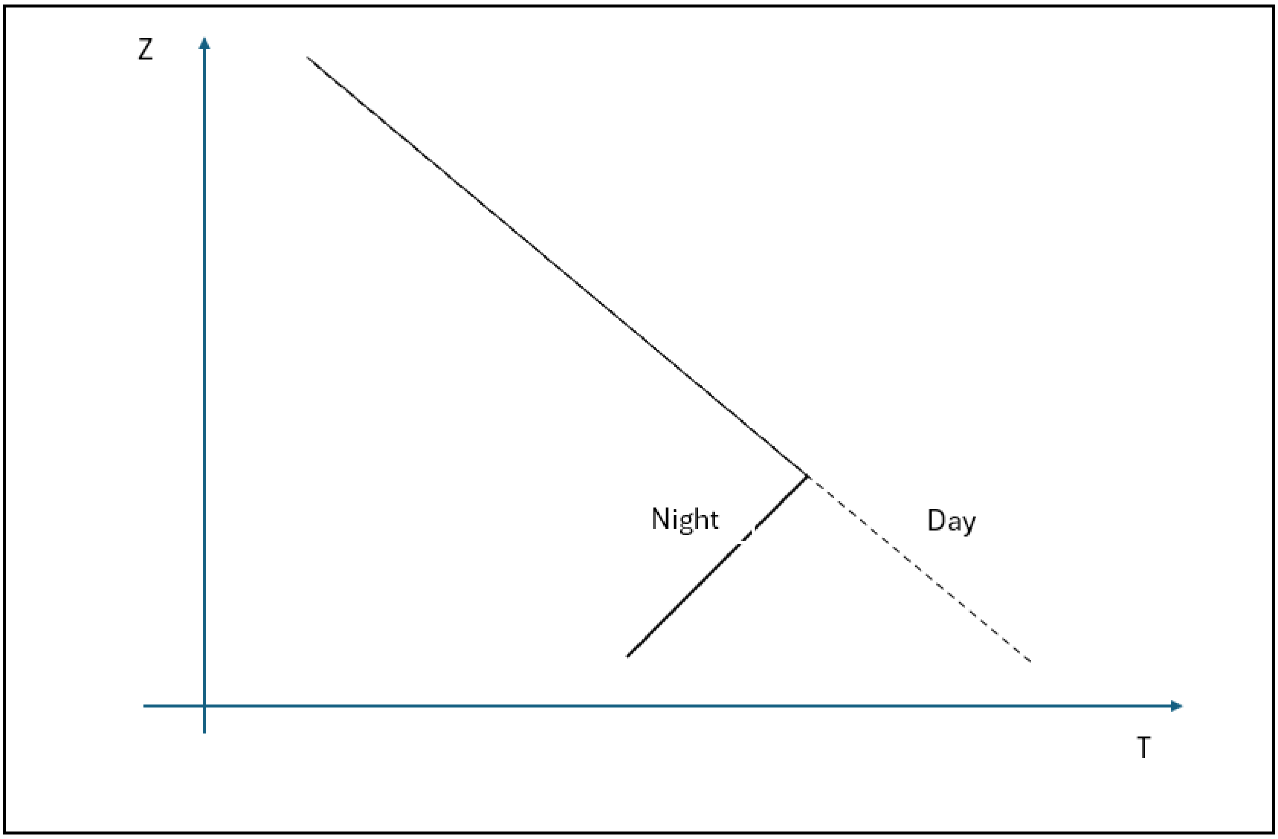


Figura 5: Thermal Inversion Condition

6.2. Pasquill Stability Classes

In light of the previous discussions, several methods have been proposed to classify atmospheric stability. In 1961, Pasquill proposed the following atmospheric stability classes:

Wind Speed (m/s)	Day, Insolation			Night	
	Strong	Average	Weak	>50% cloud cover	<50% cloud cover
<2	A	A-B	B	-	-
2-3	A-B	B	C	E	F
3-5	B	B-C	C	D	E
5-6	C	C-D	D	D	D
>6	C	D	D	D	D

These classes include three for instability (A, B, C), one for neutrality (D), and two for stability (E and F).

The class selection, including in the StackCalc software, should be made based on wind speed, the intensity of solar radiation during the day, and sky clarity at night.

These classes are still widely used today to classify weather conditions. Specifically, they are used to determine the atmospheric dispersion coefficients related to the Gaussian model implemented in StackCalc, which is described further below.

6.3. Wind Speed

Another crucial factor influencing the dispersion of effluents is wind speed. Wind has a dynamic behavior that significantly affects the shape and behavior of the plume. As mentioned earlier in Chapter 3.3, wind speed varies with altitude. Since wind speed is typically measured at an altitude of 10 meters, the wind speed at any given altitude can be estimated using the following relationship:

$$u = u_{10} * \left(\frac{H}{10}\right)^{\propto} \tag{6.4}$$

Where:

- u = wind speed at the chimney exit point (m/s
- u_{10} = wind speed specified at 10 meters above the ground (m/s)
- H = height of the stack (m)
- ∝ = parameter depending on the atmospheric stability class:
    - 0.12 for Class A (strongly unstable)
    - 0.16 for Class B (moderately unstable)
    - 0.2 for Class C (slightly unstable)
    - 0.25 for Class D (neutral)
    - 0.3 for Class E (slightly stable)
    - 0.4 for Class F (stable)

Understanding wind direction is also crucial, as it indicates the distribution of force across different directions. To achieve this, polar diagrams are used, which display the probability of wind intensity across various directions. These diagrams help visualize how wind strength varies depending on the direction and are essential for accurately assessing dispersion patterns.

6.4. Topography

The morphology of the terrain is also important as it can significantly influence the dispersion of pollutants. Lakes and seas, the presence of populated areas, or natural obstacles such as mountains or valleys can impact atmospheric turbulence and consequently the shape and behavior of the plume.

For example, the presence of a building alters the distribution of wind speeds, creating vortices that affect the dispersion of the effluent.

6.5. Plume Rise and Shape

Initially, the gases exiting the chimney will tend to rise due to the various factors mentioned earlier. This results in an apparent increase in the height of the stack, which positively affects the dispersion of the effluents.

This behavior can be explained by the temperature difference between the emitted gases and the surrounding air: hot gases, being less dense, tend to rise, creating a plume that rises above the chimney. This rise increases the vertical distance between the emission source and the ground level, promoting greater dilution of pollutants in the atmosphere and, consequently, reducing their impact at ground level.

Initially, the gases have an exit velocity with a purely vertical component; later, this is combined with the horizontal component due to the wind, resulting in a curved trajectory for the gas.

Due to the factors described in the previous paragraphs, the actual rise of the plume can also be further influenced by external factors, such as weather conditions, the previously mentioned wind speed, atmospheric stability, and the surrounding topography. For example, under conditions of strong wind or thermal inversion, the plume rise may be limited or even negated, leading to reduced dispersion of pollutants and a possible increase in their concentration at ground level. Therefore, it is essential to consider these factors in environmental impact assessments and emission management strategies

In any case, the vertical buoyancy of the gas can either be completely mechanical or dependent on the temperature of the exiting gases.

Generally, if the temperature difference between the gases exiting the stack and the ambient air is less than 50°C, the emissions are considered cold. In this case, the rise of the plume is entirely mechanical, and the elevation of the plume above the emission point can be estimated using the following formula:

$$\Delta H = D_u * \left(\frac{V_u}{u}\right)^{1.4} \tag{6.5}$$

Where

- ΔH = rise of the plume relative to the emission point, in meters;
- Du = diameter of the stack exit section, in meters;
- Vu = velocity of the gases calculated at the stack exit section, in m/s;
- u = wind speed, calculated at the altitude corresponding to the stack exit section, in m/s;

If the temperature difference exceeds 50°C, influence due to atmospheric conditions must be considered. Under stable conditions, the rise of the plume can be estimated using the following formula:

$$\Delta H = 2.6 * \left(\frac{F}{s*u}\right)^{1/3} \tag{6.6}$$

Where

$$F = g * V_u * \left(\frac{D_u}{2}\right)^2 \frac{T_u - T_a}{T_a} \tag{6.7}$$

- Con g = gravitational acceleration constant, in m/s²
- T_u = temperature of the gas at the exit point, in K
- T_a = temperature of the air calculated at the altitude corresponding to the exit point, in K

Finally, s denotes the stability parameter, which determines if the atmosphere is stable. It is defined by the following equation:

$$s = \frac{g}{T_a}\left(\frac{dT}{dZ} - \left(\frac{dT}{dZ}\right)_{ad}\right) \tag{6.8}$$

Where $\left(\frac{dT}{dZ}\right)_{ad}$ is the adiabatic descend rate, equal to 0.01 K/m, as previously described.

If s=0, the atmosphere is neutral; if s>0, the atmosphere is stable; and if s<0, the atmosphere is unstable. In the latter case, the height of the plume can be calculated using the following equation:

$$\Delta H = 1.6 * F^{1/3} * \left(\frac{3.5x_*}{u}\right)^{2/3} \tag{6.9}$$

With $x_* = 14F^{5/8}$ if F<=55 and

$x_* = 34F^{2/5}$ if F>55.

Finally, the <u>effective stack height</u> is defined as the sum of the height of the chimney and the height of the plume:

$$H_E = H_{stack} + \Delta H \tag{6.10}$$

6.6. Pasquill-Gifford Gaussian Dispersion Model

To predict the concentration of pollutants emitted into the atmosphere, StackCalc uses the Pasquill-Gifford Gaussian dispersion model.

The model is based on the assumption that the pollutant concentration distribution follows a Gaussian distribution in both horizontal and vertical directions. This means that the concentration of a pollutant disperses in the atmosphere following a Gaussian bell curve, with the highest concentration at the center of the dispersion plume and a gradual decrease in concentration as one moves away from the center.

The model focuses on several key parameters:

- **Point Source:** It is assumed that the pollutant source is a point source, as is the case with a chimney. However, the model is also applicable to any other emission concentrated at a specific point.
- **Average Wind:** The dispersion is assumed to be influenced by wind speed and direction, which carry the pollutant along the prevailing wind direction.
- **Dispersion Parameters:** These parameters describe the width of the dispersion plume in both horizontal and vertical directions. Being a Gaussian model, this is represented by the standard deviations σ_y and σ_z , which vary with distance from the source and atmospheric conditions.
- **Atmospheric Stability Categories:** As described in previous sections, Pasquill introduced a classification of atmospheric conditions into six stability classes (A to F), which influence σ_y e σ_z.
- **Release Height:** The height at which the pollutant is released above the ground is crucial for determining the vertical distribution of the concentration.

6.6.1. Equation of the model

The concentration $C(x, y, z)$ at a certain distance from the source can be expressed by the following equation::

$$C(x, y, z) = \frac{Q}{2\pi u \sigma_y \sigma_z} \exp\left(-\frac{y^2}{2{\sigma_y}^2}\right)\left[\exp\left(-\frac{(z-H_E)^2}{2{\sigma_z}^2}\right) + exp\left(-\frac{(z+H_E)^2}{2{\sigma_z}^2}\right)\right] \tag{6.11}$$

Where

- $C(x, y, z)$ is the pollutant concentration as a function of the coordinates x, y and z;
- Q is the weight flowrate of the polluttant;
- u is the average wind speed along the x direction;
- σ_y e σ_z are the standard deviation in lateral direction (y) and vertical (z), describing the dispersion of the plume;
- $H_E = H_{stack} + \Delta H$ is the effective height of the stack.

From equation 6.11, it is possible to derive all specific cases of interest. Currently, StackCalc allows the calculation of the concentration at points C(x, 0, 0), which correspond to the ground-level concentration profile along the wind direction.

6.6.2. Dispersion Parameters

StackCalc calculates the dispersion parameters σ_y e σ_z based on the Pasquill stability class, using the following expressions:

Condizioni atmosferiche	$\boldsymbol{\sigma_y}$	$\boldsymbol{\sigma_z}$
A	$\sigma_y = \frac{0.22x}{1+0.0001x}$	$\sigma_z = 0.2x$
B	$\sigma_y = \frac{0.16x}{1+0.0001x}$	$\sigma_z = 0.12x$
C	$\sigma_y = \frac{0.11x}{1+0.0001x}$	$\sigma_z = \frac{0.08x}{1+0.0002x}$
D	$\sigma_y = \frac{0.08x}{1+0.0001x}$	$\sigma_z = \frac{0.06x}{1+0.00015x}$
E	$\sigma_y = \frac{0.06x}{1+0.0001x}$	$\sigma_z = \frac{0.03x}{1+0.0003x}$
F	$\sigma_y = \frac{0.04x}{1+0.0001x}$	$\sigma_z = \frac{0.016x}{1+0.0001x}$

6.6.3. Limitations

The model has the following limitations:

- **Constant Wind Conditions.** The model assumes that the wind speed in the considered direction is always constant;
- **Absence of Chemical Reactions.** The model does not account for chemical reactions during the dispersion of pollutants.
- **Flat Terrain.** The model implemented in StackCalc does not consider the presence of complex terrains (such as very tall buildings, mountains, or significant depressions).