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INTRODUCTION
A computer software program, Wet-Cooling Tower Performance Evaluation (WCTPE), analyzes the thermal performance of counterflow and crossflow wet-cooling towers. Figure 1 shows an example of a typical natural draft counterflow cooling tower while figures 2 and 3 show examples of mechanical draft counterflow and crossflow towers respectively.

Figure 1: Natural draft counterflow wet-cooling tower.

For counterflow cooling towers the program is essentially a one-dimensional approach, that yields results orders of magnitude faster than full-blown two-, or three dimensional computational models involving the continuity, momentum and energy equations. However, the two- and three-dimensional nature of the problem is accounted for in some of the semi-empirical relations such as those for the loss and transfer coefficients in the rain zone.
Due to the iterative processes involved throughout the solution of the program, mathematical control measures are applied to prevent numerical instability and hence divergence of the solution.

Figure 2: Mechanical draft counterflow wet-cooling tower.

Figure 3: Mechanical draft crossflow wet-cooling tower.
Warnings that occur during the solution process are written to an output file. Some of these warnings occur when empirical relations are employed outside their range of applicability according to one or more variables. Warnings also occur when convergence of iterative processes is not attained in a specified maximum number of iterations within the specified solution tolerances. There are more than fifty different warnings and a possible remedy or remedies are given for each warning that is written to the warnings output file.

Some functions and variable inputs of the program are disabled for certain choices made in the program. This is done to make the software user friendly and to prevent confusion, as only the active parts of the program requires input from the user.

*Please note that this manual may not correspond 100% to your version of the software. Please contact us at info@wetcooling.com if you have any questions.*
INSTALLATION

You will receive the program files on a CD or DVD disk. There are seven files:

1. WCTPE.exe
2. WetCooling.exe
3. config.wct
4. mech_counter.txt
5. mech_cross.txt
6. natural.txt

The function of each of these files is discussed in another section. All the files must be copied to the same folder on the hard drive of a PC. To start the program, double click with the mouse on the WetCooling.exe file. All working files must always be in the same folder as the two executable files (.exe). There can be copies of the program files in multiple folders.
ASSUMPTIONS AND SIMPLIFICATIONS

It is mentioned in the introduction that the program is virtually a one-dimensional model of cooling tower operation. This can only be achieved by introducing assumptions and simplifications such as,

• The cooling tower operates under steady-state conditions without wind.
• Miscellaneous thermal loads such as make-up water additions, pump head gain and the net heat exchange with the ambient surroundings are negligible.
• Uniform air and water flow rates over the tower cross sectional area.
• For counterflow towers, the thermodynamic properties of the upward airflow and downward water flow vary vertically, but are constant across any cross section inside the tower.
PROGRAM FILES

A description of the files contained on the installation disk (or as received by email) and the files created by the program are presented next:

**UserManual.pdf**
The user’s manual is contained in this file. It is in Microsoft Word format.

**WetCooling.exe**
The *Wet-Cooling.exe* file is the main program file that must be executed from the Windows™ environment. This file contains the Graphical User Interface (GUI). All the input into the program is done from this program. The solution process is also started from this program file.

**config.wct**
`config.wct` is the configuration file. The file is called every time that the *WetCooling.exe* file is opened. All the program settings are stored in this file. This file can be changed by the user by making changes to the dialog windows shown in figures 4 to 15. If the ‘SAVE config’ button is pressed in figure 4, the `config.wct` file will be automatically updated with the settings and values entered into figures 4-15.

**WCTPE.exe**
The WCTPE.exe file contains the numerical solution algorithms. The WetCooling.exe executable file calls this executable file when the *Solve* button, shown in figure 4, is pressed.
**WARNINGS.txt**

The *WARNINGS.txt* file is created every time the program runs. This file contains warning messages that are triggered during program execution.

**Input files**

Depending on the tower configuration, the following files will be created by the *WetCooling.exe* executable file:

- InputAmbientDraft.txt
- Inputcontrol.txt
- Inputcrossflow.txt
- Inputfan.txt
- Inputlosskoef.txt
- Inputoptimization.txt
- Inputspecs.txt

These files are used as input to the *WCTPE.exe* executable file. These files can be deleted by the user without any loss of information.

**supsat.txt**

The *supsat.txt* file is created when the Poppe method is employed for counterflow configurations. If the air is unsaturated at the air outlet side of each constant water temperature interval, then a ‘0’ will be printed in the *supsat.txt* file. If the air is supersaturated a ‘1’ will appear. For example: for 5 intervals where the air is getting saturated with water vapor at the air outlet side of the third interval the *supsat.txt* will have the following contents when transposed: 0 0 1 1 1. The number of intervals is specified at input 3 in figure 8.

**Optimization files**

Some files are created when the optimization processes are employed during program execution. These files record the iterative
convergence of the optimization processes. Depending on which optimization algorithm is employed, the files are:

- Approx.out
- DynamicQ.out
- Etopc.out
- Lfopc.out
- ObjectiveFunction.txt
- OUTPUT.RESULTS

There are generally not any useful data in these files and it can be deleted without any loss of information.

**Example files**

Three example files are included:

- natural.txt
- mech_counter.txt
- mech_cross.txt

These files contain examples for a natural draft counterflow tower, mechanical draft counterflow tower and mechanical draft crossflow tower respectively. The *natural.txt* file is the same as the default *config.wct* file.

It is highly recommended that when a natural draft tower, mechanical draft counterflow or mechanical draft crossflow are designed, that these files are used as a starting point. Run the analysis often as variables are changed so that it is known which variables cause problems in program execution.
PROGRAM FEATURES

The software is generally very user friendly. If no inputs are needed in certain fields of the dialog windows, then these fields will be disabled.

*It is, however, important that no fields for variables are left empty, even if the variable will not be employed in the analysis, as this will cause the program to abort.*

When files are read into the program, the files must be in the same working directory as the executable files.

SI units are assumed for all user input, unless otherwise specified.

Due to the simplifications and assumptions made in the development of the software, the program has its limitations. Notwithstanding, it is still a very useful tool to predict cooling tower performance. It is also a very useful tool to conduct parametric studies of cooling tower performance and behavior. Parametric studies can be conducted quickly and efficiently with adequate control on the solution process.
PROGRAM DIALOG WINDOWS

This section contains all the dialog windows of the software. Each dialog window will be shown followed by a discussion of the functions and features contained within that particular dialog window. Where necessary, the input boxes and functions will be numbered. A description of each number will be presented.

MAIN PROGRAM

Figure 4 shows the main dialog window of the computer program after the WetCooling.exe program file is executed from the Windows™ environment.

The type of tower to be analyzed can be selected by selecting the appropriate radio button in figure 4. The options are:
- natural draft counterflow
- mechanical draft counterflow
- mechanical draft crossflow

The toolbar on top of the dialog box consists of many different buttons. Some of these toolbar buttons can also be accessed from the buttons presented in the left-hand part of the dialog window. Dialog windows for the specification of the atmospheric conditions, tower specifications, solution control, loss coefficients, transfer characteristics, heat and mass transfer model settings and fan specification are accessed from the main dialog window by clicking the appropriate buttons with a computer mouse.

If the 'SAVE config' toolbar button is pressed it will save all the program settings in the config.wct file. Each time the program is
opened, the values stored in the config.wct file are read automatically into the program.

All the program settings can also be saved in any user-specified file. Enter any file name in the appropriate field and press the Save button. The program settings can also be retrieved by entering the file name, which contains the previously saved settings. Then press the Open button.

Figure 4: Main dialog window of the WCTPE computer software.
AMBIENT CONDITIONS

Figure 5: Dialog window to specify ambient conditions.

1 ⇒ Atmospheric pressure, Pa or N/m²
2 ⇒ Ambient temperature, K (or °C depending on software version), measured at ground level.
3 ⇒ Dry adiabatic lapse rate, K/m

The *inlet humidity* can be expressed as one of the following:
4 ⇒ Wetbulb temperature, K (or °C depending on software version)
5 ⇒ Relative humidity, %
6 ⇒ Humidity ratio, kg/kg dry air

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Five different variations of the vertical atmospheric profiles of temperature and humidity can be specified. The first three options only influence the draft through the tower due to the vertical pressure distribution on the outside of the tower. For each of these options, the type of humidity ratio and temperature profiles can be chosen. The last two options where a temperature inversion (stable boundary layer, or SBL) is present influences both tower draft and the effective air inlet temperature and humidity. When a SBL is present, a constant humidity ratio can be chosen, or one specified by a polynomial function.

The rest of the variables specified are only relevant if a temperature inversion is present.

The reference height is the height at which the air temperature at ground level is measured. This is generally between 1 and 2 m.

The approach height is the height from which the ambient air is drawn into the cooling tower. This height is generally half the height of a natural draft tower shell. This height can be higher or lower than the inversion height.

**Inversion height**

The inversion height can be specified explicitly.

The inversion height can also be calculated by empirical equations.

The height of the inversion is taken at the height where the gradient of the temperature profile is equal to the modulus of the DALR specified in 3.

A simplified model to determine the inversion height is employed when this option is selected. If it is selected then only 14 and 15 are relevant. If it is not chosen, a more complex model is employed and 14 to 18 are relevant.
The time in hours after sunset or the diurnal temperature maximum.

Thermal eddy diffusivity, m$^2$/s. Values of 0.3 to 0.5 have been observed by other researchers.

The maximum daily temperature, °C.

The tolerance between consecutive iterations to achieve numerical convergence when the height of the inversion is iteratively determined.

The maximum number of iterations to achieve convergence.

**Exponent of inversion equation**

The value of the exponent, $b$, can be approximated by an intrinsic function by supplying the day of the year in the southern hemisphere.

The value of the exponent can be explicitly specified.

**Humidity profile**

The humidity ratio vertical profile can be specified by a polynomial as a function of height.

Specify the number of intervals for employment into the Simpson algorithm. The pressure distribution on the outside of the tower is a function of the both the temperature and humidity ratio profiles. The pressure distribution function is numerically integrated using the composite Simpson rule.
SOLUTION CONTROL AND DRAFT OPTIONS

Control Variables

The software solves five variables by iterative means and is called the solution variables. These variables are:

- water outlet temperature, Two
- mean air-water vapor mass flow rate through the fill, mav15
- dry-bulb air temperature above the fill, Ta5
- air pressure above the fill, pa5
- air pressure at cooling tower outlet, pa6
Solution control

1 ⇒ The maximum number of allowed iterations of the main solution algorithm to reach numerical convergence.

2 ⇒ The tolerances between consecutive iterations to reach convergence for the abovementioned solution variables.

3 ⇒ Mathematical control measures must be implemented to prevent instability of the iterative process. One way of preventing instability is the implementation of relaxation. During the iterative solution of the algebraic equations, it is often desirable to slow down the changes, from iteration to iteration, in the values of the solution variables. It was found that relaxation values of 0.1 for all the selected solution variables prevented divergence for most problems. It may be necessary in some cases to select smaller values, to prevent numerical instability. It is, however, desirable to have these relaxation variables as large as possible, not only to ensure quick results, but also to ensure adequate convergence.

4 ⇒ In order for the program to start the iterative process successfully, initial estimates must be supplied for the five solution variables. The user can either supply these initial values, or the program can approximate it.

5 ⇒ A filename can be specified by the user to write the output data to. This file can be appended each time the program is executed, or it can be overwritten. The default file name is output.txt. If the output file is already open, program execution will fail.

Draft options

6 ⇒ The draft (or air flow rate) can be calculated if it is unknown, which is usually the case. However, the dry air mass flow rate can be specified. This will omit the draft equation in the analysis. The user can then omit the specification of all the loss coefficients, if the draft is specified.
**Detail equation:** The detailed equation accounts for the following in the determination of the air flow rate:
- moist air that is raised in a gravitational field
- adiabatic cooling of the air
- condensation of the air as it is cooled

The detailed equation is more applicable to natural draft cooling towers, although it can be used at any time. The results obtained are generally within close tolerance of those obtained by the *Simple equation*.

**Simple equation:** The simple draft equation employs the pressure differential by only considering the density of the air after the fill and at the outside of the tower at ground level. This is the most common equation used by cooling tower designers. It is however a simplified version of the detailed equation.
TRANSFER CHARACTERISTICS

Figure 7: Dialog window to transfer coefficients.

1 ⇒ The transfer characteristic, or Merkel number (per meter fill height, m⁻¹) can be explicitly specified. Alternatively, it can be given by empirical equations. The empirical equation is specified in 7, 8 and 9. With the Empirical equation selection the Fill database number in 6 can be selected.

2 ⇒ The transfer coefficient of the spray zone (per meter fill height, m⁻¹) can be explicitly specified or defined by an intrinsic function.

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3 ⇒ The transfer coefficient of the rain zone (per meter fill height, m\(^{-1}\)) can be explicitly specified or defined by an intrinsic function. If the intrinsic empirical function is chosen then the mean drop diameter of the droplets in the rain zone must be specified.

4 ⇒ If a pure counterflow rain zone exists then it can be included in the analysis. The height of the pure counterflow region must be specified.

5 ⇒ If the water surface tension and evaporation rate of the cooling water is different from that of distilled water, then it can be quantified. All the transfer coefficients are then adjusted. For the evaporation rate the percentage specified is the percentage that the evaporation rate is more than that of distilled water. If 0 % is selected, there is no difference between the evaporation rates of cooling water and distilled water. The surface tension of the cooling water can be specified as a percentage of the surface tension of distilled water. If 100 % is specified for the surface tension then there is no difference between the surface tensions of the cooling water and distilled water.

*Fill specification*

6 ⇒ The transfer coefficient of the fill can be selected from a database of published data. Refer to Appendix A for the selection of available fills.

7 ⇒ The transfer coefficient of the fill can also be specified by selecting a particular form of the empirical equation. The coefficients can be entered in the relevant text boxes.

8 ⇒ The loss coefficient can be specified in the same manner as the transfer coefficient in 7. Refer to figure 13, input 3, for the activation of the fill loss coefficient specification.
The transfer coefficient of the fill specified above can be offset by a preset percentage. The transfer coefficients published in the literature are generally obtained by employing the Merkel model. If the Poppe model is employed the transfer coefficient must be increased by approximately 7 to 9 %. If the e-NTU model is employed the transfer coefficient must be decreased by approximately 1 to 2 %. These offset percentages are obtained from our experience. It may be possible that these percentages are different for the conditions that you specify.
COUNTERFLOW TRANSFER MODEL SETTINGS

Figure 8: Dialog window to specify counterflow heat and mass transfer model settings.

1. Choose the heat and mass transfer model. It is important that the transfer coefficient specified in figure 7 is derived using the same heat and mass transfer model; otherwise it must be adjusted as explained in 9 in the previous section.
If you use the Poppe method then it is recommended that the values in inputs 2 to 7 are kept unchanged. Only change these values in consultation with us.

2 ⇒ The maximum number of internal iterations in the Poppe model.
3 ⇒ The number of intervals that the fill is divided into.
4 ⇒ The minimum tolerance of the temperature between consecutive iterations to reach convergence.
5 ⇒ The minimum tolerance of the outlet humidity between consecutive iterations to reach convergence.
6 ⇒ The Secant differential is a parameter that aids in the determination of two initial approximations for the water outlet temperature for the Secant iterative scheme.
7 ⇒ The governing equations for heat and mass transfer can be solved by different numerical schemes. The one scheme employs a Secant iterative method. In the other scheme the governing equations is derived in another form and solved without the Secant method. These options are separately available when the water inlet temperature or heat rejection rate is known. To choose whether the water inlet temperature or heat rejection rate is known please refer to figures 10, 11 and 12 (input 1).
8 ⇒ The Lewis factor can be specified by the equation of Bosnjakovic. The Lewis factor can also be specified as a constant, or it can be determined by another empirical equation that is a function of the Lewis number, where the exponent must be specified. This exponent is generally given as 0.667.
9 ⇒ For the Merkel approach, the numerical integration algorithm can be selected. The four point Chebyshev numerical integration method is the preferred algorithm for cooling tower analyses according to international standards, but the Simpson algorithm is also included in the program for comparative purposes as the number of numerical integration intervals can be specified.
Different energy equations can be used the Merkel approach to calculate the air temperature above the spray zone.

**Common energy equation:** This equation is commonly used in the published literature to calculate the air outlet temperature. This energy equation does not account for the change in the water mass flow rate due to evaporation. This consideration has far reaching implications for especially natural draft towers, where the draft through the tower is a function of the air temperature above the spray zone.

**Improved energy equation:** We first published the improved equation and it does account for the evaporated water in the energy equation.

The variables specified for the *e-NTU* approach are parameters to control an internal Secant iterative procedure. The Secant differential is a parameter to determine two initial approximations for the water outlet temperature for the Secant iterative scheme.
CROSSFLOW TRANSFER MODEL SETTINGS

Figure 9: Dialog window to specify crossflow heat and mass transfer model settings.

1 ⇒ Choose the required heat and mass transfer model.
2 ⇒ Choose the number intervals to divide the fill into. The height and the width of the fill are divided into equal intervals.

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3 ⇒ The maximum number of internal iterations for a Secant iterative scheme to calculate the water outlet temperature.
4 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the water outlet temperature.
5 ⇒ The Secant differential is a parameter that aids in the determination of two initial approximations for the water outlet temperature for the Secant iterative scheme.
6 ⇒ Specify the maximum number of iterations for a Secant iterative scheme to calculate the transfer coefficient.
7 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the transfer coefficient.
8 ⇒ The Secant differential is a parameter that aids in the determination of two initial approximations for the transfer coefficient for the Secant iterative scheme.
9 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the air enthalpy, water outlet temperature and humidity ratio.
10 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the transfer coefficient.
11 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the air enthalpy. The unit for this tolerance is J/kg. Since the enthalpy of air is generally in the order of $10^6$ J/kg, the tolerance can be set relatively high (200-300), otherwise the maximum number of iterations will be reached without convergence.
12 ⇒ Specify the maximum allowable tolerance between two consecutive iterations to achieve convergence for the humidity ratio.
The settings for the Merkel model are exactly the same as the corresponding settings for the Poppe approach given above.

Select whether the air and water streams are mixed, unmixed or a combination of the two.

Due to the crossflow configuration, a 2-d solution is obtained. This lends itself to the graphical presentation of the results. If this option is chosen a file, *Tecplot.txt*, will be generated in TECPLOT format. For the Merkel method the water temperature and air enthalpy fields are included. For the Poppe method the water temperature, air enthalpy, water mass flow rate, Lewis factor, humidity ratio, state of the air and air temperature fields are included. The state of the air plots whether the air is supersaturated or unsaturated. If the air is supersaturated in a particular cell in the solution domain, or fill, then a ‘1’ will be plotted. A ‘0’ will be plotted if the air is unsaturated.
COOLING TOWER DIMENSIONS

Mechanical draft counterflow tower

Figure 10: Dialog window to specify counterflow mechanical draft tower dimensions and operating conditions.

1 ⇒ Select whether the water inlet temperature or the total heat rejection rate is known. (The unit of temperature is K or °C depending on software version)
2 ⇒ Specify the inlet water mass flow rate.
3 ⇒ Specify the height of the plenum chamber.
4 ⇒ Specify the height of the spray zone.
5 ⇒ Specify the height of the fan above ground level.
6 ⇒ Specify the fill height.
7 ⇒ Specify the height of the air inlet.
8 ⇒ Specify the frontal area of the fill.
9 ⇒ Specify the breadth of the tower (into the page).
10 ⇒ Specify the width of the tower.
11 ⇒ Specify the inlet rounding radius. This dimension is required to calculate the cooling tower inlet loss coefficient, Kct.
12 ⇒ Specify the total height of the cooling tower.
Natural draft counterflow tower

Figure 11: Dialog window to specify natural draft tower dimensions and operating conditions.

1 ⇒ Select whether the water inlet temperature or the total heat rejection rate is known.
2 ⇒ Specify the inlet water mass flow rate.
3 ⇒ Specify the diameter of the tower shell at the outlet of the tower.

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4 ⇒ Specify the height of the tower shell above ground level.
5 ⇒ Specify the diameter of the tower shell lip diameter.
6 ⇒ Specify the height of the spray zone.
7 ⇒ Specify the height of the fill.
8 ⇒ Specify the inlet height of the cooling tower.
9 ⇒ Specify the frontal area of the fill.
10 ⇒ Specify the shell thickness at the bottom lip if the shell.
11 ⇒ Specify the inlet rounding radius. This dimension is required to calculate the cooling tower inlet loss coefficient, Kct.
Mechanical draft crossflow

Figure 12: Dialog window to specify crossflow mechanical draft tower dimensions and operating conditions.

1 ⇒ Select whether the water inlet temperature or the total heat rejection rate is known.
2 ⇒ Specify the inlet water mass flow rate.
3 ⇒ Specify the width of the tower (into the page).
4 ⇒ Specify the air travel distance, ATD.
5 ⇒ Specify the total height of the tower.
6 ⇒ Specify the height of the fan.
7 ⇒ Specify the height of the fill.
LOSS COEFFICIENTS

Only the dialog window for the specification of the loss coefficients of mechanical draft towers are shown. The specification of the loss coefficients for the natural draft cooling tower is exactly the same as the mechanical draft towers except that the input in 11 to 14 in figure 13 are omitted.

![Figure 13: Dialog window to specify loss coefficients.](image)

1 ⇒ Specify the loss coefficient due to the tower supports. The loss coefficient can be explicitly specified, or it can be determined by a semi-empirical equation by specifying the number, length, diameter and drag coefficient of the tower supports. If the pressure losses due to the tower supports can be neglected, then the coefficient can be set to zero. This is applicable to all loss coefficients.

2 ⇒ Specify the loss coefficient due to the drift eliminator. The loss coefficient can be specified directly or it can be determined by an empirical relation. If the latter option is chosen then the coefficients of the empirical relation must be specified.
3 ⇒ Specify the fill loss coefficient explicitly or by an empirical equation. If the empirical equation option is selected then the fill loss coefficient can be specified by the same manner as the fill transfer coefficient in figure 7. If a number from the fill database is selected at 6 in figure 7, then it include both the transfer and loss coefficients. The empirical relation for the loss coefficient can also be explicitly specified at 8 in figure 7.

4 ⇒ Specify the tower inlet losses explicitly or by an empirical equation.

5 ⇒ Specify the loss coefficient in the rain zone explicitly or by an empirical equation. A pure counterflow rain zone can also be included in the analysis. The height of the counterflow rain zone is specified at 4 in figure 7.

6 ⇒ Specify the loss coefficient of the spray zone explicitly or by an empirical equation.

7 ⇒ Specify the expansion losses as the air expands as it exits the fill. The loss coefficient can be specified explicitly or by an empirical equation.

8-15 ⇒ Inlet louvre, fill support, water distribution system, fan upstream, fan downstream, plenum, diffuser and contraction losses are specified in 8 to 15. No empirical relations are available in the program to specify these loss coefficients. These loss coefficients can only be specified explicitly. 11 to 14 are only applicable to mechanical draft cooling towers. These options do not appear in the dialog window when a natural draft tower is selected in the main program dialog, shown in figure 4.
Figure 14: Dialog window to specify fan for mechanical draft towers.

1 ⇒ Specify the fan static pressure as a sixth order polynomial. The fan static pressure is a function of the volume flow rate \((VFr, \text{m}^3/\text{s})\) through the fan. \(VFr\) is the volume flow rate for the fan model specified in 12-14.

2,3 ⇒ Specify fan power and fan efficiency as sixth order polynomials in the same manner as the fan static pressure in 1. The specifications of fan power and fan efficiency can be omitted if it is not available.
has no bearing on the overall results of the program. The fan power and efficiency are given in the output file specified at 5 in figure 6.

4 ⇒ Specify the number of fans in the cell.
5 ⇒ Specify the fan speed in rpm.
6 ⇒ Specify the fan diameter.
7 ⇒ Specify the fan casing diameter.
8 ⇒ Specify the fan hub diameter.
9 ⇒ Specify the fan diffuser diameter.
10 ⇒ Specify the kinetic energy velocity distribution coefficient at the diffuser outlet.
11 ⇒ Specify the kinetic energy velocity distribution correction factor at the outlet of the fan.
12 ⇒ Specify the fan model diameter.
13 ⇒ Specify the density at which the fan model was tested.
14 ⇒ Specify the speed at which the fan model was tested.
15 ⇒ A database of fans can be built by saving the fan specifications entered in the dialog window shown in figure 14. All the data that appear on the dialog window will be saved into the file specified by the user. The data that appears in the dialog window will also be saved in the main program settings file, specified by the user, in the main dialog window shown in figure 4.
Figure 15: Dialog window to specify optimization settings.

1 ⇒ Select an optimization problem.

*Optimize (Lfi)*: If this option is chosen, the optimum fill height will be determined for the fill specified in figure 7. This is only a thermal and not a cost optimization. **At the optimum fill depth the maximum amount of air will flow through the tower while the water is cooled to the minimum temperature for the specific fill height.** It is essentially the lowest possible temperature that is possible for a specific cooling tower. If the fill depth is increased beyond this optimal depth, the extra heat and mass transfer due to the added transfer area does not
make up for the reduced airflow due to the extra air resistance. This optimization does not necessarily leads to practical (usable) cooling towers and may only be of theoretical value. An initial value of the fill height has to be specified at 7 in figure 11.

**Optimize cost:** This option will determine the optimum shape of a natural draft cooling tower to obtain the minimum combined operational and capital cost over the projected life of the cooling tower. Input options 11-21 will be enabled. The water inlet and water outlet temperatures are known. The shape of the tower is optimized for the minimum cost to obtain a prescribed cooling rate. Initial values for the fill height, tower inlet diameter, tower height and air inlet height have to be specified at 7, 5, 4 and 8 in figure 11 respectively. After program execution the tower dimensions that give the optimum tower cost will be given in the console window. An example of the console window is given in figure 16.

2 ⇒ There is a choice between two optimization algorithms. Input options 3-10 are the settings of both optimization algorithms.
3 ⇒ The convergence tolerance on the function value.
4 ⇒ Convergence tolerance on the step movement.
5 ⇒ Convergence tolerance on the norm of the gradient.
6 ⇒ The maximum step size.
7 ⇒ The maximum number of steps per phase.
8 ⇒ The finite difference interval used to calculate derivatives. This value should be chosen as small as possible but large enough to prevent instability.
9 ⇒ The initial penalty value. Its default value is 100. A value of 10 is usually accurate for engineering applications and leads to faster solution times.
10 ⇒ The maximum penalty value. The default value is 10000. A value of 100 is usually accurate for engineering applications and leads to faster solution times.

11 ⇒ Specify the cost of electricity.

12 ⇒ Specify the total amount of hours that the tower will operate in a year.

13 ⇒ Specify the inflation rate of the cost of electricity.

14 ⇒ Specify the investment period or the economic life of the cooling tower.

15 ⇒ Specify the cost of concrete per cubic meters.

16 ⇒ Specify the cost of the fill material per cubic meters.

17 ⇒ Specify the ratio of the tower outlet to inlet diameters to prevent cold inflow into the cooling tower.

18 ⇒ Specify the percentage area the fill will occupy relative to the total available area. This will allow for space for the fill support structure and water distribution system.

19 ⇒ Specify the interest rate at which the money is borrowed from the bank.

20 ⇒ Specify the water outlet temperature.

21 ⇒ Inequality constraints are specified here to ensure that physically realistic results are obtained and to prevent any numerical instability in the program. The inlet height, H3, must be greater or equal to the specified value. The total height of the tower, H6, is also constrained to prevent a tower height that is not feasible.
**EXAMPLE PROBLEM**

Load the `natural.txt` file into the program if the `config.wct` file is not in its original format. Press the *Solve* button in the main dialog window shown in figure 4.

*Console Window*

A console window will be automatically opened where the progress of the solution process is shown. If the program executes successfully, the most significant output variables are shown. An example of the console window for the natural draft tower is shown in figure 16. Depending on the program settings and hardware configuration of your PC the numerical values of the output may differ slightly.

```
ITERATION 85 0.000E+00 0.000E+00 0.000E+00 0.781E-02 0.391E-02
ITERATION 86 0.000E+00 0.305E-04 0.000E+00 0.781E-02 0.391E-02
ITERATION 87 0.000E+00 0.000E+00 0.000E+00 0.000E+00 0.000E+00

CONVERGENCE REACHED AFTER 87 ITERATIONS

MERKEL = 1.46042

<table>
<thead>
<tr>
<th>EVAP = 308.03799 KG/S</th>
<th>ME_FI = 0.93142</th>
<th>ME_RZ = 0.41418</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q = 971.24139 MW</td>
<td>ME_SP = 0.11482</td>
<td>ME_RZC = 0.00000</td>
</tr>
<tr>
<td>MAV15 = 16767.94336 KG/S</td>
<td>KILFI = 0.00000</td>
<td>KFSFI = 0.23927</td>
</tr>
<tr>
<td>TWO = 294.55417 K</td>
<td>KCTCFI = 0.23927</td>
<td>KCTEFI = 0.00109</td>
</tr>
<tr>
<td>TA5 = 299.60693 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA5 = 83937.96875 PA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PA6 = 82650.64844 PA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>W5 = 0.268186E-01 KG/KG</td>
<td></td>
<td></td>
</tr>
<tr>
<td>RANGE = 18.59583 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRFT_L = 68.81734</td>
<td></td>
<td></td>
</tr>
<tr>
<td>DRFT_R = 68.81739</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MERKEL = 1.46042</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

!!** NO WARNINGS **!!

TYPE ENTER TO CONTINUE
```

Figure 16: Example of the console widow after a successful program execution.

© Copyright 2009 wetcooling software & consulting
Here follows a description of the information contained on the console window:

1 ⇒ The iteration number is given together with the residual values of the five solution variables shown in figure 6. The variables from left to right are Two, Ta5, pa5, pa6 and mav15. If all the residual values are less than the tolerances specified at 2 in figure 6, then convergence is reached.

2 ⇒ The message shown here will indicate how many iterations were necessary to achieve convergence. If the maximum number of iterations, specified at 1 in figure 6, are reached before convergence is attained then the message will indicate that.

3 ⇒ The particular heat and mass transfer model that were chosen at 1 in figure 8 for counterflow and figure 9 for crossflow, is shown here.

4 ⇒ A selected few solution variables are shown here. A complete list of solution variables can be found in the output file specified at 5 in figure 6. An example of such a file is presented in the next section. The variables given here are the total heat transfer rate, Q, the average air water-vapor mass flow rate between the air inlet and the outlet of the spray zone, mav15, the outlet water temperature, Two, the air pressure above the sprays, pa5, the air pressure at the inside top of the tower shell, pa6, and the humidity ratio above the sprays. Range is the cooling range of the water. DRFT_L and DRFT_R are the left-hand side and the right-hand side of the draft equation respectively. These quantities must be approximately equal. Merkel is the total of the Merkel numbers in the spray zone, rain zone and fill. If a stable boundary layer was chosen at 7 in figure 5, then three additional variables are shown, i.e., the height of the inversion, zit, the effective inlet temperature into the tower, Tcm, and the value of the exponent b that is employed in the determination of the temperature inversion profile.
5 ⇒ The values of the Merkel numbers in the respective transfer areas are shown. ME_FI, ME_SP and ME_RZ are the Merkel numbers in the fill, spray zone and rain zone respectively. ME_RZC is the Merkel number of the pure counterflow rain zone specified at 4 in figure 7.

6 ⇒ The values of most of the loss coefficients, referred to conditions in the fill, are presented here.

7 ⇒ The number of warnings that are evoked during the last iteration of program execution is shown here. See the section on the warning messages for more details.

8 ⇒ Type enter to close the console window. The console window must be closed before the next program can be solved.

**Output File**

A complete list of solution variables are given in the output file specified at 5 in figure 6. Next is an example of the output file. The temperatures may be expressed in K or in C depending on your version of the software.
The selected heat and mass transfer model.

The chosen ambient conditions.

The solution variables as explained at 4 in figure 16.

Some water properties.

The values of the loss coefficients, referred to conditions in the fill are given first. The second value is the percentage for a particular loss coefficient of the total loss coefficient.

The Merkel numbers in the respective transfer areas.

The mass flow rates of the air. MA is the dry air mass flow rate. MAV1 and MAV5 is the air water vapor mass flow rates at the inlet of the tower and at the top of the sprays respectively. MAV15 is the average of MAV1 and MAV5.

The ambient vapor pressure and the humidity ratio are given.

Thermophysical properties of the air-vapor mixture at the inlet of the tower.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AIR INLET TEMPERATURE [TA1]</td>
<td>288.60001</td>
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<tr>
<td>WETBULB TEMPERATURE [TWB]</td>
<td>284.19998</td>
</tr>
<tr>
<td>ATMOSPHERIC PRESSURE [PA1]</td>
<td>84100.00000</td>
</tr>
<tr>
<td>MASS FLOW RATE [MAV15]</td>
<td>16767.94336</td>
</tr>
<tr>
<td>PRESSURE [PA5]</td>
<td>83937.96875</td>
</tr>
<tr>
<td>TEMPERATURE [TA5]</td>
<td>299.60693</td>
</tr>
<tr>
<td>TEMPERATURE [TWO]</td>
<td>294.55417</td>
</tr>
<tr>
<td>PRESSURE [PA6]</td>
<td>82650.64844</td>
</tr>
<tr>
<td>HUMIDITY [W5]</td>
<td>0.026818635</td>
</tr>
<tr>
<td>EVAPORATION RATE [MWVAP]</td>
<td>308.03799</td>
</tr>
<tr>
<td>HEAT REJECTED [Q]</td>
<td>971.24139</td>
</tr>
<tr>
<td>WATER SPECIFIC HEAT [CPWM]</td>
<td>4178.32031</td>
</tr>
<tr>
<td>OUTLET WATER DENSITY [RHOWO]</td>
<td>997.86371</td>
</tr>
<tr>
<td>WATER MASS VELOCITY [GW]</td>
<td>1.50602</td>
</tr>
<tr>
<td>WATER OUTLET TEMP [TWO]</td>
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</tr>
<tr>
<td>INLET LOUVER [KILFI]</td>
<td>0.00000</td>
</tr>
<tr>
<td>FILL SUPPORT STRUCTUR [KFSFI]</td>
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<td>CONTRACTION LOSSES [KCTCFI]</td>
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<tr>
<td>EXPANSION LOSSES [KCTEFI]</td>
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<tr>
<td>SPRAY ZONE [KSPFI]</td>
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<tr>
<td>WATER DISTRIBUTION [KWDFI]</td>
<td>0.52201</td>
</tr>
<tr>
<td>DRIFT ELIMINATOR [KDEFI]</td>
<td>5.47531</td>
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<tr>
<td>FILL [KFI]</td>
<td>3.92693</td>
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<tr>
<td>RAIN ZONE [KRZFI]</td>
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<tr>
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</tr>
<tr>
<td>TOWER SUPPORTS [KTSFI]</td>
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</tr>
<tr>
<td>TOTAL [KTOTAL]</td>
<td>24.49919</td>
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<tr>
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<tr>
<td>RAIN ZONE ME [MERZ]</td>
<td>0.41418</td>
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<tr>
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</tr>
<tr>
<td>TOTAL MERKEL NUMBER [LINKS]</td>
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</tr>
<tr>
<td>MASS FLOW RATE [MA]</td>
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<tr>
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</tr>
<tr>
<td>MASS FLOW RATE [MAV5]</td>
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</tr>
<tr>
<td>MASS FLOW RATE [MAV15]</td>
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</tr>
<tr>
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<tr>
<td>HUMIDITY [W]</td>
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<tr>
<td>AIR-VAPOR DENSITY [RHOAV1]</td>
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<tr>
<td>SPECIFIC HEAT OF AIR [CPA1]</td>
<td>1006.43982</td>
</tr>
<tr>
<td>SPECIFIC HEAT OF VAPOR [CPV1]</td>
<td>1869.19910</td>
</tr>
<tr>
<td>AIR-VAPOR ENTHALPY [IMA1]</td>
<td>36114.69922</td>
</tr>
</tbody>
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VAPOR PRESSURE \[ PV5 \] = 3452.38379
HUMIDITY \[ W5 \] = 0.026818635
HUMIDITY \[ WSA5 \] = 0.027452961
AIR-VAPOR DENSITY \[ RHOAV5 \] = 0.96065
SPECIFIC HEAT OF AIR \[ CPA5 \] = 1006.55188
SPECIFIC HEAT OF VAPOR \[ CPV5 \] = 1873.82715
AIR-VAPOR ENTHALPY \[ IMAS5 \] = 95049.28906

Thermophysical properties of the air-vapor mixture above the sprays.

PA1 - PA7 \[ PA1-7 \] = 1445.73438
PA1 - PA34 \[ PA1-34 \] = 111.29469
PA34 - PA6 \[ PA34-6 \] = 1269.27539
PA6 - PA7 \[ PA6-7 \] = -3.65305
LHS DRAFT EQUATION \[ LHS \] = 68.81734
RHS DRAFT EQUATION \[ RHS \] = 68.81739
FAN EFFECTIVENESS \[ EF \] = 0.00000
FAN POWER \[ PF \] = 0.00000
TWI \[ TWI \] = 313.14999
RELATIVE HUMIDITY \[ RH1 \] = 0.61834
HEIGHT OF INVERSION TOP \[ ZIT \] = 0.00000
DRY AIR MASS VELOCITY \[ GA \] = 1.98554

PUMP POWER \[ KW \] = 15317.40039
TOTAL PUMP OPERAT. COST \[ MS \] = 1524.55090
CONCRETE VOLUME \[ M3 \] = 38180.48438
TOWER COST \[ MS \] = 3.81805
FILL VOLUME \[ M3 \] = 20783.19922
FILL COST \[ MS \] = 1.66266
TOTAL CAPITAL COST \[ MS \] = 729.89569
MINIMUM INVESTMENT \[ MS \] = 2254.44653

This last section has to do with the optimization of the cooling tower. If the optimization option is not selected from the main dialog window then these results will show the costs for the tower according to the values in figure 15.

MS is million dollars or any other currency.
WARNING MESSAGES

Warning messages are triggered during program execution if certain preset conditions are violated. These warning messages are written to the WARNINGS.txt file. Only the warning messages given at the last iteration in the WARNINGS.txt file is of any concern.

Types of Warnings

There are two general types of warnings:

1. The first type of warning has to do with the convergence of the solution. This type of warning occurs when the maximum number of iterations is reached before convergence is attained inside one of the many iterative schemes employed in the program.

2. The second type of warning is where some empirical equations are employed outside the allowable range of one or more of the variables contained inside the empirical equations. These warning messages are only informative and no remedial measures are required from the user. The value of the variable, which is used outside its allowable range is written to the WARNINGS.txt file together with the allowable range of application of the particular variable. The user can then make an estimate of how accurate the results are.

WARNING 0 to WARNING 16

WARNING 0 to WARNING 16 are warnings where the maximum number of iterations is reached before convergence. Possible remedial measures are suggested in the WARNINGS.txt file to prevent the warning messages. Possible remedies for all of these warnings are to increase the maximum allowable number of iterations.
or by relaxing solution tolerances pertaining to the specific iterative scheme.

**WARNING 17 to WARNING 36**
WARNING 17 to WARNING 36 are warnings for variables, used outside their allowable range, contained in the empirical equations that calculate the loss and transfer coefficients in the rain zone of *natural draft* cooling towers.

**WARNING 37 to WARNING 52**
WARNING 37 to WARNING 52 are warnings for variables, used outside their allowable range, contained in the empirical equations that calculate the loss and transfer coefficients in the rain zone of *counterflow mechanical draft* cooling towers.

**WARNING 53 to WARNING 55**
WARNING 53 and WARNING 54, for natural draft and mechanical draft tower respectively, are warnings that inform the user that the tower is operating at air and water flow conditions not typically found in industry. WARNING 55 warns that the maximum number of iterations is reached when the inversion height is calculated. No user input is necessary.

**WARNING 56 and WARNING 57**
WARNING 56 and WARNING 57 warn that corrective measures are implemented that prevent negative square roots in the solution algorithm. These warnings, if triggered, should generally only be encountered during the first few iterations.
CONTACT DETAILS

Although the program is thoroughly tested, it is inevitable that some bugs or errors may be present in the program. If errors are detected or you require any details or user support, please contact me at the email address given below. The level of technical support that I offer is dependent on the package that you have purchased.

I will come back to you as soon as possible.

Dr J.C. Kloppers

Email: info@wetcooling.com

Postal address:
P.O. Box 131137
Bryanston
2021
South Africa
APPENDIX A

FILL TRANSFER & LOSS COEFFICIENT DATABASE

Introduction

The transfer coefficient and pressure coefficient data for fills in the database in the software (Figure 7, Input No 6) are presented in this appendix. The transfer characteristic and pressure drop data in this appendix are adapted from Kröger [1]. The original data is published in Lowe and Christie [2] and Johnson [3]. All data is obtained by using Merkel’s theory.

The data of 56 different fills are included in the software. The fill database number in the software must correspond to the fill type number in the tables below. Fill type numbers from 1 to 49 are for counterflow fills. Fill types from 50 to 56 are for crossflow cooling towers.

How to use this appendix

Select the fill type number in the tables below. Please note that there are counterflow and crossflow fills in the tables. Every fill type corresponds to a figure number. The figures are given below the tables. The fill type from the tables is the fill database number that is entered into the software.
References


DATA FOR COUNTERFLOW FILLS

All the subsequent tables are adapted from Kröger [1].

<table>
<thead>
<tr>
<th>Fill type</th>
<th>Description</th>
<th>Fig. no.</th>
<th>Dimensions</th>
<th>Mass Transfer</th>
<th>Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$a_a$ m</td>
<td>$P_a$ m</td>
<td>$P_l$ m</td>
</tr>
<tr>
<td>1</td>
<td>Triangular splash bar</td>
<td>Staggered</td>
<td>0.1524</td>
<td>0.2286</td>
<td>0.2950</td>
</tr>
<tr>
<td>2</td>
<td>Triangular splash bar</td>
<td>Staggered</td>
<td>0.1524</td>
<td>0.1524</td>
<td>0.3084</td>
</tr>
<tr>
<td>3</td>
<td>Triangular splash bar</td>
<td>Staggered</td>
<td>0.1524</td>
<td>Altern 0.1270 0.3302</td>
<td>0.3150</td>
</tr>
<tr>
<td>4</td>
<td>Triangular splash bar</td>
<td>Staggered</td>
<td>0.1524</td>
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<td>6</td>
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<td>0.0444</td>
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<td>0.0381</td>
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<table>
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<th>Fig. no.</th>
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<th>Mass Transfer</th>
<th>Pressure</th>
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<td>$P_l$ m</td>
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<td>----------</td>
<td>------------</td>
<td>---------------</td>
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</tr>
<tr>
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<td>$P_a$ m</td>
<td>$P_l$ m</td>
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<table>
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<tr>
<th>Description</th>
<th>Fig. no.</th>
<th>Dimensions</th>
<th>Mass Transfer</th>
<th>Pressure</th>
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</thead>
<tbody>
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<td>36</td>
<td>Corrugated asbestos sheets</td>
<td></td>
<td>0.0540</td>
<td>0.1461</td>
</tr>
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<td>37</td>
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<td>0.0730</td>
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### Mass transfer per meter of fill height or ATD, \( h_{dl}/G_w = a_d (G_w/G_a)^{b_{da}} \) ATD^{b_{db}}

### Loss coefficient per meter of fill height or ATD, \( K_{fl} = a_p (G_w)^{b_{pa}} (G_a)^{b_{pb}} \) ATD^{b_{pc}}

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Fig.</th>
<th>Description</th>
<th>Size(s) tested, ( H,W,ATD ) [m]</th>
<th>( a_d )</th>
<th>( b_{da} )</th>
<th>( b_{db} )</th>
<th>( a_p )</th>
<th>( b_{pa} )</th>
<th>( b_{pb} )</th>
<th>( b_{pc} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>42</td>
<td>14</td>
<td>American Tower Plastics Cool Drop</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 2.0, 2.8 ) and 3.4</td>
<td>0.710</td>
<td>-0.42</td>
<td>-0.50</td>
<td>2.880</td>
<td>0.85</td>
<td>-0.690</td>
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<td>43</td>
<td>15</td>
<td>Ecodyne Shape10</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 1.829, 2.438 ) and 3.353</td>
<td>0.605</td>
<td>-0.35</td>
<td>-0.42</td>
<td>1.103</td>
<td>1.10</td>
<td>-0.640</td>
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<tr>
<td>44</td>
<td>16</td>
<td>Toshi Fiber Cement (Dimpled and Unslotted)</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 1.22, 1.62 ) and 2.03</td>
<td>1.169</td>
<td>-0.64</td>
<td>-0.51</td>
<td>0.621</td>
<td>0.99</td>
<td>-0.350</td>
<td>0.17</td>
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<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Fig.</th>
<th>Description</th>
<th>Size(s) tested, ( H,W,ATD ) [m]</th>
<th>( a_d )</th>
<th>( b_{da} )</th>
<th>( b_{db} )</th>
<th>( a_p )</th>
<th>( b_{pa} )</th>
<th>( b_{pb} )</th>
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</tr>
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<tbody>
<tr>
<td>45</td>
<td>17</td>
<td>Munters 12060</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 0.609, 0.914 ) and 1.524</td>
<td>2.490</td>
<td>-0.67</td>
<td>-0.062</td>
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<td>46</td>
<td>18</td>
<td>Munters 19060</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 0.914, 1.524 ) and 2.134</td>
<td>1.597</td>
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<td>-0.19</td>
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<td>47</td>
<td>19</td>
<td>American Tower Plastics Cool Film</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 1.0, 1.5 ) and 2.0</td>
<td>2.138</td>
<td>-0.56</td>
<td>-0.38</td>
<td>7.821</td>
<td>0.23</td>
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<tr>
<td>48</td>
<td>19</td>
<td>Marley MC67</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 0.914, 1.219 ) and 1.524</td>
<td>1.495</td>
<td>-0.63</td>
<td>-0.35</td>
<td>7.089</td>
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<td>-0.140</td>
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<tr>
<td>49</td>
<td>20</td>
<td>Brentwood Ind Accu-Pak CF1900</td>
<td>( H_x = 2.438 \times 2.438 ) ( ATD = 0.914, 1.524 ) and 2.134</td>
<td>1.664</td>
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<td>-0.27</td>
<td>3.691</td>
<td>0.31</td>
<td>-0.099</td>
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</tbody>
</table>

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# DATA FOR CROSSFLOW FILLS

Mass transfer per meter of fill height, \( h_{d,\text{lt}}/G_w = \frac{h_{d,\text{lt}}(\text{ATD} \times \text{width})}{m_w} = a_d \left( \frac{G_w}{G_a} \right)^{b_d} \)

Loss coefficient per meter of air travel distance (ATD) in fill, \( K_{\text{fl}} = a_p \left( \frac{G_w}{G_a} \right) b_{\text{fl}} \)

<table>
<thead>
<tr>
<th>Fill Type</th>
<th>Fig.</th>
<th>Description, spacing [mm]</th>
<th>Airflow orientation</th>
<th>Fill configuration</th>
<th>Size(s) tested, HxWxATD [m]</th>
<th>( a_d )</th>
<th>( b_d )</th>
<th>( a_p )</th>
<th>( b_{\text{pa}} )</th>
<th>( b_{\text{pb}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>10</td>
<td>Doron V-bar, 101.6x203.2</td>
<td>Parallel</td>
<td>Staggered</td>
<td>3.658x2.438x1.829</td>
<td>0.268</td>
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<td>Doron V-bar, 203.2x203.2</td>
<td>Parallel</td>
<td>In-line</td>
<td>3.658x2.438x1.829</td>
<td>0.239</td>
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<td>11</td>
<td>Ecodyne T-bar, 101.6x203.2</td>
<td>Parallel</td>
<td>Staggered</td>
<td>3.658x2.438x1.829</td>
<td>0.263</td>
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<td>In-line</td>
<td>3.658x2.438x1.829</td>
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<td>12</td>
<td>Wood lath, 101.6x101.6</td>
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<td>0.274</td>
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<td>12</td>
<td>Wood lath, 101.6x101.6</td>
<td>Perpendicular</td>
<td>Staggered</td>
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<tr>
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<td>13</td>
<td>Marley Alpha-bar, 101.6x406.4</td>
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<td>Staggered</td>
<td>3.658x2.438x1.829</td>
<td>0.307</td>
<td>-0.052</td>
<td>1.816</td>
<td>0.71</td>
<td>-0.85</td>
</tr>
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</table>
FILL FIGURES

All the fills on this page are counterflow fills, i.e. figure number 1 to 9.

1

2

3

4

5

6

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8

9

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Figures 10 to 13 are crossflow fills while figures 13 and 14 are counterflow fills.
All the fills on this page are counterflow fills, i.e. figures 16 to 20.