COMPUTER ASSISTED CALCULATIONS OF PSYCHROMETRIC PROPERTIES OF HUMID AIR

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ABSTRACT

The psychrometric properties of humid air can be predicted either analytically by recourse to the laws for gases or by consulting specially prepared charts and tables. Analytical calculations are time consuming and most of the psychrometric charts available in the references are based on sea level properties. Therefore, finding psychrometric properties from zero-altitude charts can create errors. In this study, seven main properties of the psychrometrics, namely dry-bulb, wet-bulb and dew-point temperatures, atmospheric pressure, humidity ratio, relative humidity and enthalpy can be calculated using the given procedures. A computer program on calculation procedures of psychrometric properties is written in VisualBASIC and their applications are shown in various examples. The program also calculates the properties of water, air and refrigerants ammonia, R12, R22, R23, R32, R125, R134a, R143a as pure substances and converts units.

INTRODUCTION

Psychrometry is the study of the behavior of mixtures of gas (non-condensable) and vapors (condensable), in particular systems of air and vapor. Principles of psychrometry apply to humidification and dehumidification, air conditioning, cooling, cold storage, drying and many other phenomena involving condensation and evaporation of water.

In general, the psychrometric properties of a medium can be predicted either analytically by recourse to the laws for gases or by consulting specially prepared charts and tables. Using these charts, if the atmospheric pressure or altitude is known, it is easy to find the psychrometric properties using two other known properties. However, for instance during the designing of a cold store, in most cases its altitude is different from sea level. And yet, most of the charts available in the references are based on sea level properties. Therefore, finding psychrometric properties from zero-altitude charts can create errors. Although the best method for finding these properties is to calculate them analytically using the perfect gas relationships, in many situations, it is often neither convenient nor practical. A realistic solution for these problems is to employ a computer for the numerical solution of the relevant equations: the psychrometric properties being defined in the software (1).

Thermodynamic parameters of the atmosphere form part of the input to numerical forecasting models. Usually these parameters are evaluated, as stated above, from a thermodynamic diagram whereas Devres (1) and Babu (2) developed a technique to evaluate these parameters using a Fortran program. The calculations with their models were tested and the results were found in agreement with the results from the conventional method.

Zhang *et al.* presented a technique for selecting psychrometric equations and their solution order (3). In their study, they expressed that if atmospheric pressure, dry-bulb temperature and relative humidity were known and it was desired to determine the other 12 psychrometric attributes, then there are approximately 37 780 different orders in which to solve the equations to determine the other parameters. The task of identifying these many possible combinations of equations, and selecting an appropriate one, is called a decision problem in computation theory. One technique for solving decision problems is a Turing machine computational model. They have constructed a Turing machine, which they referred to as a Psychrometric Turing Machine (PTM), to solve all possible psychrometric problems. The PTM selects the optimal equation order based upon a user-specified optimality criterion of CPU cycles (3).

A neural network approach was used for the prediction of the psychrometric parameters in a non-iterative manner by Sreekanth *et al.* (4). In their study neural network models were developed for each of the three main variables - dry bulb temperature, wet-bulb temperature and relative humidity - as a function of the other two variables. The prediction accuracy of their models was found to be very good, with errors less than 4% (4).

During the psychrometric calculations, thermophysical properties of water should be known. There are several sources for obtaining properties of water. One of them, the STEAM database is the U.S. implementation of an international standard. Some of the thermophysical properties covered in this software include temperature, pressure, volume, quality, enthalpy, entropy, thermal conductivity, viscosity, dielectric constant, and surface tension (5, 6).

There are several softwares on psychrometry where some of them can be reached through Internet:

1. WinMetric: In this software when two independent properties of the initial state are presented as input, the program will calculate all remaining properties. Demo version can be downloadable (7).
2. PsychTools™: Windows (95/98, NT) based software for performing quick and easy psychrometric calculations on a PC. Values for air temperature, moisture content, elevation, and volumetric flow rate are being entered into the program. Moisture content of the air can be entered in any appropriate IP (English) or SI (metric) unit. The program calculates the wet bulb temperature, dew point, RH, humidity ratio, enthalpy, and specific volume. Air volumes can be entered in actual units or standard units and are output in both units. Units can be instantaneously switched with a

click of the mouse allowing the program to also function as a conversion utility. Shareware version is available to download (8).

3. PsyCalc: Calculates eight properties by just inputting two. This site also offers free psychrometric chart, psychrometric program, psychrometric excel functions, Psychrometric Function DLL, Psychrometric Java Applet. Shareware versions are downloadable (9).
4. Psychrometric Program: This program provides psychrometric properties of air by giving two properties as input values at a known altitude (or atmospheric pressure). The properties are determined using the ideal gas law as the behavior of air. Once the properties are determined, the point is indicated on the psychrometric chart. Process lines can be connected between any two known points; this will provide the user with the difference in moving from one point to the next. Additionally, this program will allow the user to perform some basic HVAC calculations that depend on the psychrometrics. Free demonstration version of this program is available online (10).
5. Get Psyched! : Program allows to calculate psychrometric properties in MS Excel. It calculates enthalpy, dew-point temperature, relative humidity, humidity ratio, specific volume, wet-bulb temperature. The chart will be automatically corrected basing on any altitude that is selected up to 30 000 ft. Shareware version can be downloadable (11).
6. Psychrometric calculator: Any two known properties among dry-bulb, wet-bulb and dew-point temperatures and relative humidity are chosen as an input to calculate remaining properties. It is also possible to change the altitude. Online calculations are possible (12). Previous version can be used on-line in other mirror sites (13, 14).
7. TEST (The Expert System for Thermodynamics©): This program covers various applets in thermodynamic applications including psychrometry developed by Bhattacharjee (15). It works on-line.
8. Psychrometric calculator: A Java applet developed by Engineering Exchange that employs any known three properties and calculates remaining properties on-line (16).

The purpose of the present study is to develop a PC based psychrometry program where the former one written in Fortran for mainframe computer (1). The program can be applied in calculation of psychrometric properties while designing a project that employs humid air as a working substance. Using this utility, the assignment problems in Thermodynamic courses in ITU, Food Engineering Department are also defined to enhance instruction technique in teaching of thermodynamics.

METHOD

Psychrometric equations

There are seven main different properties in the psychrometric charts, namely, dry-bulb, wet-bulb and dew-point temperatures, atmospheric pressure, humidity ratio, relative humidity and enthalpy (1, 17). According to the Gibbs Phase Rule, there are four degrees of freedom for a system consisting of humid air, assuming it to be a mixture of nitrogen, oxygen, and water vapor. For all practical purposes the ratio of the masses of oxygen and nitrogen in air is constant, hence the degrees of freedom are reduced to three. Thus any three intensive properties will be sufficient to evaluate the remaining properties. Therefore the combination of three out of seven properties gives a total of 35 different sets. These are shown in Table 1. In this study, each set is used separately in an attempt to find solutions for the remaining unknown variables. In most cases analytical solutions were not found and numerical methods had to be employed (1).

For the determination of psychrometric properties, knowledge of the water-vapor saturation-pressure is essential. The equations for calculating saturation pressures for the temperature ranges -100°C to 200°C are given in Table 2. The solutions for the saturation vapor pressure as a function of temperatures were found with REGAN (18), using polynomial REGression ANalysis on data obtained from ASHRAE (19). In some cases however, the saturation pressure was known allowing the temperature to be calculated from the data. In such cases, temperatures calculated using saturation pressures where derived from regression analysis are shown in Table 3 (1).

The definition of psychrometric properties can be given very easily where perfect gas relations are employed (17). As a result, only equations (in total 28 equations) are given in Table 4. In every equation, in order to obtain the property given in the second column, the known properties given in the third column must be replaced in the equation given in the fourth column. The units of each property are shown in the last column (1).

Recommended procedures for the calculation of psychrometric properties

Calculation procedures in step-by-step are showed in Table 5. With the following steps, it is easy to calculate the unknown properties. In most cases, however, numerical analyses must be employed for solution (1).

Programming

In the computer program, 32 out of the 35 combinations have been solved successfully. In combinations 9, 11 and 26 (see Table 5), the equations could not be solved. In each of these cases, two of the equations differed only by a numerical factor, effectively reducing the number of free parameters and not permitting non-trivial solutions (1).

Each equation encountered in the calculation procedures of thermodynamic properties of humid air was evaluated as functions or procedures using VisualBASIC programming language. In this regard approximately 58 procedures or functions and additional complementary ones were designed. While designing a form for “Properties of Fluids” tabulated data for each fluid were written as separate classes with an extension of “filename.cls” in order to keep the executable file in smaller bytes. Other utility additions were designed to enhance the applicability of the software to extensive problems encountered in engineering.

Application of the program

On the main screen of the program there are 4 menus of which are namely **File** (has submenu as “Print Results to File”, “Exit”), **Format** (has submenu as “Clock”, “Form”, “Set Objects to Null”, “Digit”), **Tools** (has submenu as “Unit Conversion”, “Fluids”, “Questions”, “Demo”, “About”) and **Help**, Fig.1.. In this menu three known properties chosen by clicking the boxes, values are filled and then "Calculate" button is pushed. Following or before this procedure, in the same menu, it is possible to change the units by left-clicking mouse in every property's right-side menu according to needs of the user.

Data used in calculation of properties of the fluids (Fig. 2.), namely water, air and refrigerants ammonia, R12, R22, R23, R32, R125, R134a, R143a are obtained from references 20-22. In this menu, saturated liquid, saturated vapor, superheated vapor properties of mentioned pure substances can be calculated according to their states.

With this program same assignments but with different data are given to students of thermodynamic courses in Istanbul Technical University, Food Engineering Department. Since the problems are same, they could collaborate with each other as they like, but everyone should have to calculate with his/her own data individually to find the right answer (23, 24). In the last two years, the program is being used successfully and effectively in courses with further updates and improvements.

RESULTS AND DISCUSSION

In this study a software to calculate psychrometric properties of humid air is developed with supplementary utilities such as unit conversion, fluid properties and example problems in psychrometry. All the properties were calculated with only small errors as done in the previous study (1) in a different platform. To enhance instruction technique in teaching of thermodynamics, the program is also employed. Some of the assignment problems in thermodynamic courses in ITU, Food Engineering Department are defined and it is being used in the past two years' courses.

NOMENCLATURE

A	Constant defined in Table 2
B	Constant defined in Table 2
C	Constant defined in Table 2
D	Constant defined in Table 2
E	Constant defined in Table 3
F	Constant defined in Table 3
G	Constant defined in Table 3
h	Enthalpy of humid air, kJ/kg
h_w*	Specific enthalpy of condensed water at the thermodynamic wet-bulb temperature and a pressure of 101 325 Pa, kJ/kg
H	Constant defined in Table 3
K	Constant defined in Table 3
p_w	Partial pressure of water vapor in humid air, Pa
p_{ws}	Pressure of saturated pure water, Pa
P	Total pressure of humid air, Pa
R_a	Gas constant for dry air, J/kg K
T	Dry-bulb temperature, °C
T*	Wet-bulb temperature, °C
T_D	Dew-point temperature, °C
v	Specific volume of humid air, m^3/kg
W	Humidity ratio of humid air, kg/kg
W_s	Humidity ratio of humid air at saturation, kg/kg
W_s*	Humidity ratio of humid air at saturation at thermodynamic wet-bulb temperature, kg/kg
α	Parameter defined in Table 2
β	Parameter defined in Table 3
ϕ	Relative humidity
μ	Degree of saturation

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Table 1. Combination sets of seven psychrometric properties, each set comprising three properties

1	T	T*	T_D
2	T	T_D	P
3	T	P	W
4	T	W	ϕ
5	T	ϕ	h
6	T	T*	P
7	T	T_D	W
8	T	P	ϕ
9	T	W	h
10	T	T*	W
11	T	T_D	ϕ
12	T	P	h
13	T	T*	ϕ
14	T	T_D	h
15	T	T*	h
16	T*	T_D	P
17	T*	P	W
18	T*	W	ϕ
19	T*	ϕ	h
20	T*	T_D	W
21	T*	P	ϕ
22	T*	W	h
23	T*	T_D	ϕ
24	T*	P	h
25	T*	T_D	h
26	T_D	P	W
27	T_D	W	ϕ
28	T_D	ϕ	h
29	T_D	P	ϕ
30	T_D	W	h
31	T_D	P	h
32	P	W	ϕ
33	P	ϕ	h
34	P	W	h
35	W	ϕ	h

T	Dry-bulb temperature
T*	Wet-bulb temperature
T_D	Dew-point temperature
P	Pressure
W	Humidity ratio
ϕ	Relative humidity
h	Enthalpy

Table 2. Calculation of water-vapour saturation pressure which is dependent on the temperature within various temperature ranges, $\alpha = A{\cdot}T^2 + B{\cdot}T + C + D{\cdot}T^{-1}$, T in K; $p_{ws} = 1000{\cdot}\exp(\alpha)$, p_{ws} in Pa

	Temperature (K)				
	$213.15 \le T < 273.15$	$273.15 \le T < 322.15$	$322.15 \le T < 373.15$	$373.15 \le T < 423.15$	$423.15 \le T < 473.15$
A	$-0.7297593707{\cdot}10^{-5}$	$+0.1255001965{\cdot}10^{-4}$	$+0.1246732157{\cdot}10^{-4}$	$+0.1204507646{\cdot}10^{-4}$	$+0.1069730183{\cdot}10^{-4}$
B	$+0.5397420727{\cdot}10^{-2}$	$-0.1923595289{\cdot}10^{-1}$	$-0.1915465806{\cdot}10^{-1}$	$-0.1866650553{\cdot}10^{-1}$	$-0.1698965754{\cdot}10^{-1}$
C	$+0.2069880620{\cdot}10^{+2}$	$+0.2705101899{\cdot}10^{+2}$	$+0.2702388315{\cdot}10^{+2}$	$+0.2683629403{\cdot}10^{+2}$	$+0.2614073298{\cdot}10^{+2}$
D	$-0.6042275128{\cdot}10^{+4}$	$-0.6344011577{\cdot}10^{+4}$	$-0.6340941639{\cdot}10^{+4}$	$-0.6316972063{\cdot}10^{+4}$	$-0.6220781230{\cdot}10^{+4}$

Table 3. Calculation of temperature which is dependent on water vapour saturation pressure within various pressure ranges, $T = E{\cdot}\beta^4 + F{\cdot}\beta^3 + G{\cdot}\beta^2 + H{\cdot}\beta + K$, T in K; $\beta = \ln(p_{ws})$, p_{ws} in Pa

	Pressure (Pa)				
	$1 \le p < 611$	$611 \le p < 12350$	$12350 \le T < 101420$	$101420 \le T < 476207$	$476207 \le T < 1555099$
E	$+0.1004926534{\cdot}10^{-2}$	$+0.5031062503{\cdot}10^{-2}$	$+0.1209512517{\cdot}10^{-4}$	$+0.2467291016{\cdot}10^{-1}$	$+0.2748402484{\cdot}10^{-4}$
F	$+0.1392917633{\cdot}10^{-2}$	$-0.8826779380{\cdot}10^{-1}$	$-0.3545542105{\cdot}10^{+0}$	$-0.9367112883{\cdot}10^{+0}$	$-0.1068661307{\cdot}10^{+1}$
G	$+0.2815151574{\cdot}10^{+0}$	$+0.1243688446{\cdot}10^{+1}$	$+0.5020858479{\cdot}10^{+1}$	$+0.1514142334{\cdot}10^{+2}$	$+0.1742964962{\cdot}10^{+2}$
H	$+0.7311621119{\cdot}10^{+1}$	$+0.3388534296{\cdot}10^{+1}$	$-0.2050301050{\cdot}10^{+2}$	$-0.9882417501{\cdot}10^{+2}$	$-0.1161208532{\cdot}10^{+3}$
K	$+0.2125893734{\cdot}10^{+3}$	$+0.2150077993{\cdot}10^{+3}$	$+0.2718585432{\cdot}10^{+3}$	$+0.4995092948{\cdot}10^{+3}$	$+0.5472618120{\cdot}10^{+3}$

Table 4. Calculation of psychrometric properties

Eq. No.	*To obtain*	*Knowns*	*Equation*	*Remarks*
1	p_{ws}	T	$\alpha = A \cdot T^2 + B \cdot T + C + D \cdot T^{-1}$	$p_{ws} = 1000 \cdot \exp(\alpha)$, T (K), p_{ws} (Pa)
2	T	p_{ws}	$T = E \cdot \beta^4 + F \cdot \beta^3 + G \cdot \beta^2 + H \cdot \beta + K$	$\beta = \ln(p_{ws})$, T (K), p_{ws} (Pa)
3	p_w	T_D	$\alpha = A \cdot T_D^2 + B \cdot T_D + C + D \cdot T_D^{-1}$	$p_w = 1000 \cdot \exp(\alpha)$, T_D (K), p_w (Pa)
4	T_D	p_w	$T_D = E \cdot \beta^4 + F \cdot \beta^3 + G \cdot \beta^2 + H \cdot \beta + K$	$\beta = \ln(p_w)$, T_D (K), p_w (Pa)
5	p_{ws}^*	T^*	$\alpha = A \cdot T^{*2} + B \cdot T^* + C + D \cdot T^{*-1}$	$p_{ws}^* = 1000 \cdot \exp(\alpha)$, T^* (K), p_{ws}^* (Pa)
6	h	T, W	$h = T + W \cdot (2501 + 1.805 \cdot T)$	T (°C), h (kJ/kg)
7	T	h, W	$T = \frac{h - 2501 \cdot W}{1 + 1.805 \cdot W}$	T (°C), h (kJ/kg)
8	W	h, T	$W = \frac{h - T}{2501 + 1.805 \cdot T}$	T (°C), h (kJ/kg)
9	W	P, p_w	$W = 0.62198 \cdot \frac{p_w}{P - p_w}$	P (Pa), p_w (Pa)
10	P	p_w, W	$P = 0.62198 \cdot \frac{p_w}{W} + p_w$	P (Pa), p_w (Pa)
11	p_w	P, W	$p_w = \frac{P \cdot W}{W + 0.62198}$	P (Pa), p_w (Pa)
12	W_s	P, p_{ws}	$W_s = 0.62198 \cdot \frac{p_{ws}}{P - p_{ws}}$	P (Pa), p_{ws} (Pa)
13	P	p_{ws}, W_s	$P = 0.62198 \cdot \frac{p_{ws}}{W_s} + p_{ws}$	P (Pa), p_{ws} (Pa)
14	p_{ws}	P, W_s	$p_{ws} = 0.62198 \cdot \frac{P - W_s}{W_s + 0.62198}$	P (Pa), p_w (Pa)
15	W_s^*	P, p_{ws}^*	$W_s^* = 0.62198 \cdot \frac{p_{ws}^*}{P - p_{ws}^*}$	P (Pa), p_{ws}^* (Pa)
16	P	p_{ws}^*, W_s^*	$P = 0.62198 \cdot \frac{p_{ws}^*}{W_s^*} + p_{ws}^*$	P (Pa), p_{ws}^* (Pa)
17	p_{ws}^*	P, W_s^*	$p_{ws}^* = \frac{P \cdot W_s^*}{W_s^* + 0.62198}$	P (Pa), p_{ws}^* (Pa)
18	W_s^*	h, W, T^*	$W_s^* = \frac{h_s^* - h}{h_w^*} + W$	$h_s^* = T^* + (2501 + 1.805 \cdot T^*) \cdot W_s^*$ $h_w^* = 4.186 \cdot T^*$; h, h_s^*, h_w^* (kJ / kg), T^* (°C)
19	W	W_s^*, h, T^*	$W = \frac{h - h_s^*}{h_w^*} + W_s^*$	$h_s^* = T^* + (2501 + 1.805 \cdot T^*) \cdot W_s^*$ $h_w^* = 4.186 \cdot T^*$; h, h_s^*, h_w^* (kJ / kg), T^* (°C)
20	W	W_s^*, T, T^*	$W = \frac{(2501 - 2.381 \cdot T^*) \cdot W_s^* - (T - T^*)}{2501 + 1.805 \cdot T - 4.186 \cdot T^*}$	T (°C), T^* (°C)
21	T^*	W_s^*, W, T	$T^* = \frac{2501 \cdot (W_s^* - W) - T \cdot (1 + 1.805 \cdot W)}{2.381 \cdot W_s^* - 4.186 \cdot W - 1}$	T (°C), T^* (°C)
22	W_s^*	W, T, T^*	$W_s^* = \frac{(2501 + 1.805 \cdot T - 2.381 \cdot T^*) \cdot W + (T - T^*)}{2501 - 2.381 \cdot T^*}$	T (°C), T^*(°C)
23	T	W_s^*, W, T^*	$T = \frac{(2501 - 2.381 \cdot T^*) \cdot W_s^* - (2501 - 4.186 \cdot T^*) \cdot W + T^*}{1 + 1.805 \cdot W}$	T (°C), T^*(°C)
24	ϕ	p_w, p_{ws}	$\phi = p_w / p_{ws}$	p_w (Pa), p_{ws} (Pa)
25	p_w	ϕ, p_{ws}	$p_w = \phi \cdot p_{ws}$	p_w (Pa), p_{ws} (Pa)
26	p_{ws}	ϕ, p_w	$p_{ws} = p_w / \phi$	p_w (Pa), p_{ws} (Pa)
27	μ	W, W_s	$\mu = W / W_s$	
28	v	T, P, W	$v = R_a \cdot T \cdot (1 + 1.6078 \cdot W) / P \quad R_a = 287.055$ (J / kgK)	v (m^3/kg), T (K), P (Pa)

Table 5. Recommended procedures for the calculation of psychrometric properties

		Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8	Step 9
No.	Knowns	Equation(s) applied in each step								
1	T, T^*, T_D	1	5	3	9,15,18	9	12	15	6	24
2	T, T_D, P	1	3	9	12	15,21	5	15	6	24
3	T, W, P	1	11	4	12	15, 21	5	15	6	24
4	T, W, ϕ	1	25	10	4	12	15, 21	5	15	6
5	T, ϕ, h	1	25	8	10	4	12	15, 21	5	15
6	T, T^*, P	1	5	15	20	12	11	4	6	24
7	T, T_D, W	1	3	10	12	15, 21	5	15	6	24
8	T, ϕ, P	1	25	9	12	4	15, 21	5	15	6
9	T, W, h	Unresolvable								
10	T, T^*, W	1	5	22	16	12	11	4	6	24
11	T, T_D, ϕ	Unresolvable								
12	T, h, P	1	8	11	4	12	15, 21	5	15	24
13	T, T^*, ϕ	1	25	4	5	9, 20	9	12	15	6
14	T, h, T_D	1	8	3	10	12	15, 21	5	15	24
15	T, T^*, h	1	8	5	22	16	11	4	12	24
16	T^*, T_D, P	3	5	15	9	23	1	12	6	24
17	T^*, P, W	11	4	5	15	23	1	12	6	24
18	T^*, W, ϕ	5	1,10,20,25	1	10, 25	12	15	11	4	6
19	T^*, ϕ, h	5	8,9,15,18,25	Apply step 2	1	12	25	4	9	15
20	T^*, T_D, W	3	10	5	15	23	1	12	6	24
21	T^*, ϕ, P	5	15	9, 20, 25	1	12	9	25	4	6
22	T^*, W, h	5	7	1	22	16	11	4	12	24
23	T^*, T_D, ϕ	3	5	26	2	9, 15, 20	9	15	12	6
24	T^*, P, h	5	15	19	11	4	7	1	12	24
25	T^*, T_D, h	5	3	9, 15, 18	9	7	1	12	15	24
26	T_D, P, W	Unresolvable								
27	T_D, W, ϕ	3	26	2	10	12	15, 21	5	15	6
28	T_D, ϕ, h	3	26	2	8	10	12	15, 21	5	15
29	T_D, P, ϕ	3	26	2	9	12	15, 21	5	15	6
30	T_D, W, h	3	10	7	1	12	15, 21	5	15	24
31	T_D, P, h	3	9	7	1	12	15, 21	5	15	24
32	P, W, ϕ	11	4	26	2	12	15, 21	5	15	6
33	P, ϕ, h	6, 9, 25	1	12	25	4	9	15, 21	5	15
34	P, W, h	7	1	11	4	12	15, 21	5	15	24
35	W, ϕ, h	7	1	25	4	10	12	15, 21	5	15

Solve resulting equation using numerical analysis (grey cells)

Solve resulting quadratic equation (black cells)

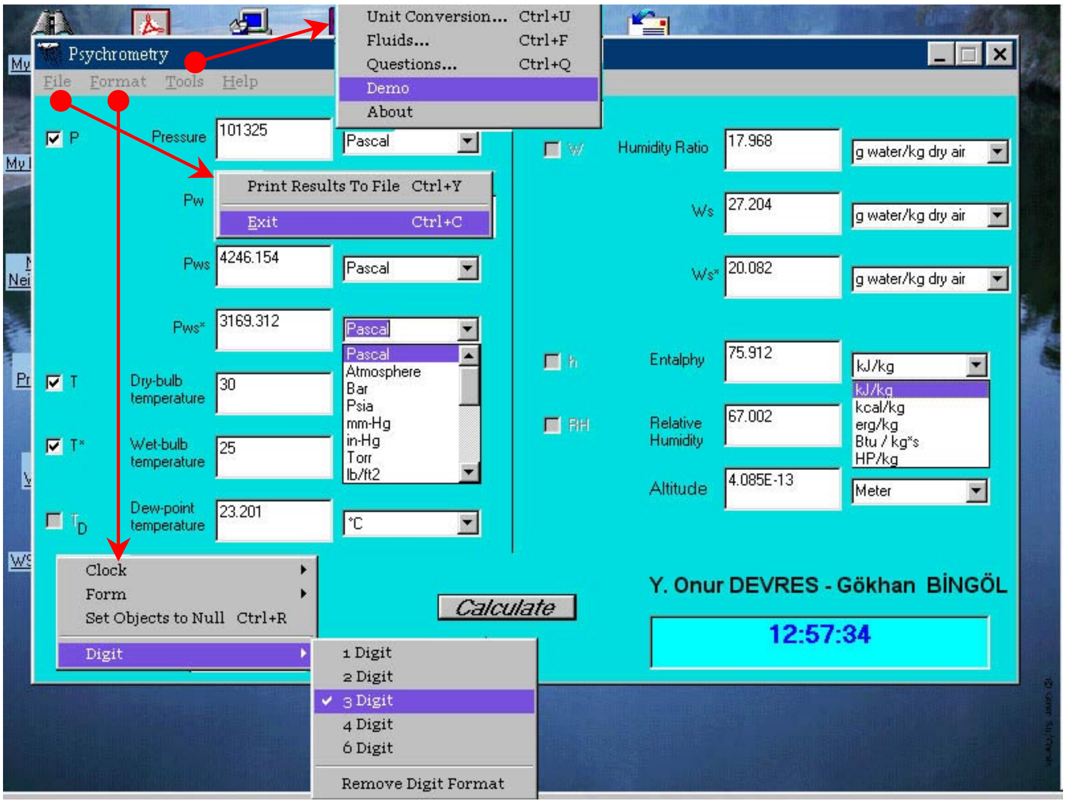

Fig. 1. Screen of the main menu and its submenus

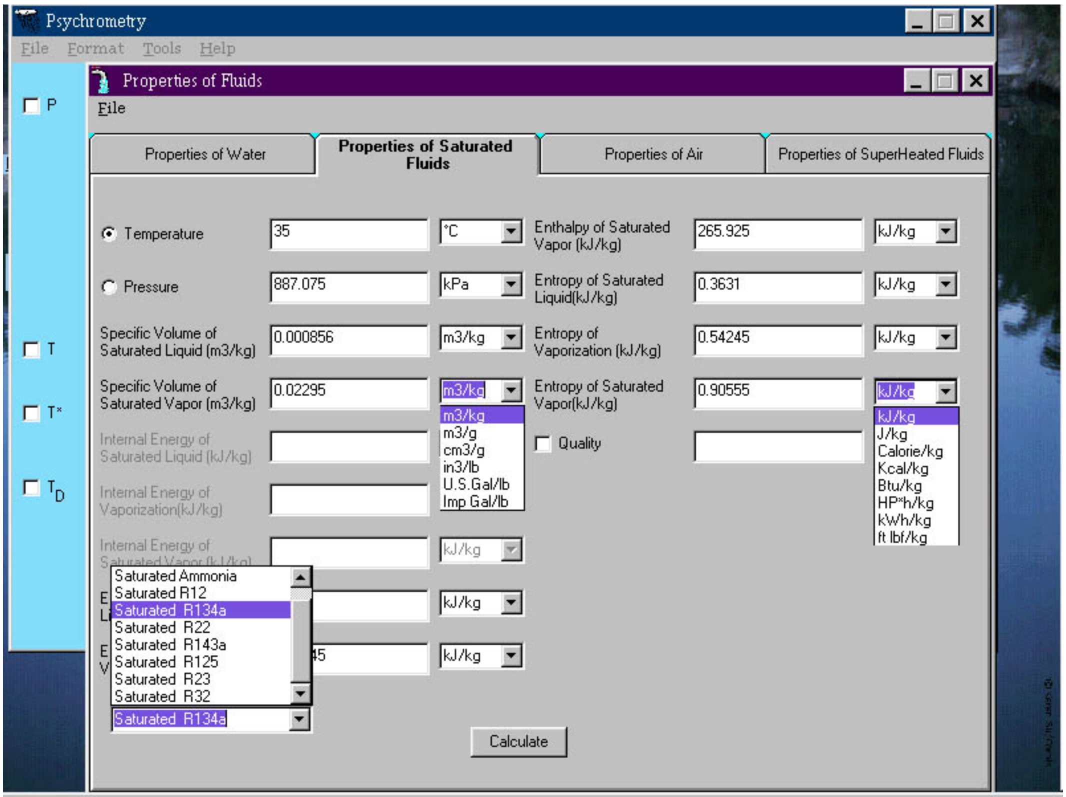

Fig. 2. Screen of the properties of fluids menu

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