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Prediction Models of Skin Temperatures and Heat Loss by Evaporation for Thermal Comfort in Buildings in Hot and Humid Climates in Cameroon

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Abstract

The aim of this study is to propose models for predicting skin temperatures and heat loss by evaporation for the inclusion in the calculations of thermal comfort indicators in hot and humid areas, more particularly in sub-Saharan Africa. This will make it possible to complete the thermal comfort data for this climatic region, which for lack of it still uses the standard based on Fanger models, established mainly for the temperate zone (ISO 7730). The experiments were carried out on a representative sample of 24 people (men and women) in experimental buildings, located in the Douala-Cameroon region, representative of the hot and humid zone, as considered by numerous thermal balance references encountered in the litterature. The measurements of the ambient parameters and of the physiological parameters were carried out according to the recommended standards. 1008 skin temperature measurement points were performed on 3 levels of metabolic activity, in order to provide 72 individual average skin temperature values. Analyzes, statistical validation tests and comparisons were performed. We are able to present the most suitable prediction models, other than those of Fanger, for thermal comfort conditions in air-conditioned buildings in hot and humid areas of sub-Saharan Africa. It appears that the skin of people living in these regions has a higher thermal inertia, less water loss by diffusion or a higher skin barrier than that of people in temperate regions.

Keywords: Skin temperature; heat loss by evaporation; hot and humid climates; skin wettedness; thermal comfort.

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1. Introduction

The need to study the thermal ergonomics of work and living spaces was triggered (around the 1910s) by three main motivations relating to the success of military activities in more or less severe hygrothermal conditions, the improvement of these conditions for the safety and performance of workers and the comfort of people in their daily life environments. Over time, many studies carried out by both analytical and experimental approaches have greatly contributed to the development of knowledge that can be found in the literature through books, journals and the works of well-known authors featured in [1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25] etc. to name a few. These studies have not only made it possible to develop criteria for evaluating hygrothermal conditions, but also to develop techniques to improve or modify them according to the environments concerned. Among the evaluation criteria are thermal comfort indicators, stress indices and thermal strain. Most of the techniques developed concern the architecture of the building for thermal comfort and energy efficiency, as well as technologies for modifying and controlling the hygrothermal parameters of work or residence spaces. In view of their analytical or statistical relevance, in [26,27,28,29,30] certain thermal indicators have been associated with satisfaction with international standards for applications extended to various types of workspaces or buildings (for thermal comfort, the risks of thermal stress and thermal strain on hot and cold). However, there remains the problem of the universality of data or models, especially when local climatic specificities become significant. Many authors have directed work in this direction and continue to update them, both in temperate regions and in hot and humid areas. In the case of temperate zones, we can easily mention the work of authors already referenced above, Fanger and his colleagues in [8,9,10,11,12], Gagge and his colleagues [13,14,15,16,17,18], Humpreys and his colleagues [19,20,21,22,23], Malchaire and his colleagues in [25] and those of Olesen in [31,32], Moujalled in [33], Holmer in [34] etc. to quote only those. In the sub-Saharan region dominated by hot and humid climates, the best-known studies are those of Y. Jannot and T. Djiako in [24], Olissan and his colleagues in [35,36], Kemajou and his colleagues in [37], Djongyang and his colleagues in [38,39], Nematchoua and his colleagues in [40] etc. There are limitations in the models proposed. Regarding the indicators of thermal stress in the workplace (IREQ index in [30]), the determination of the thermal resistance and the air permeability of certain traditional clothing remains insufficient with regard to the ISO 9920 standard in [41]; there is also an approximate estimate of the metabolism, skin temperature and heat loss by evaporation at the surface of the skin of people living under the climatic conditions to be covered. Regarding the analytical thermal comfort indices, the application of the PMV and PPD indices of the Fanger model presents limits, first of all due to the stationary and homogeneous character that the thermal environments must have (because it is expected that, if one or several variables change, the PMV can be used in the form of time-weighted average values over a period of 1 hour, according to ISO 7730 in [26]), then by the lack of local data on skin temperature and heat loss by evaporation on the surface of the skin of people living in the climatic zone referred to in this study. Gagge's dynamic thermal comfort model (SET and ET indices), however, is not used in sub-Saharan regions and also remains limited by the lack of contextual data on skin temperature and heat loss by evaporation at the skin surface of people living in this climate. On the other hand, the thermophysiological models of thermal comfort developed or presented by authors such as [42,43,44,45,46] are made complex compared to the large number of differential equations to be used. If their resolutions are not a problem because there are advanced resolution programs, the main limitation remains in the determination or statistical measurement of certain physiological parameters. Regarding the adaptive thermal comfort models developed by many authors including Humpreys and his colleagues already cited above and Busch in [47,48,49,50,51], Toffum and his colleagues in [52,53], the applications in naturally ventilated buildings present limitations through the restrictions imposed by the architecture of the building and the reductions in the opportunities for behavioral adaptation of the occupants, by the use of high ventilation speeds in hot and humid areas, with the risk of losing the comfort required for certain activities. It is important to note that in sub-Saharan Africa, adaptive models are still only applied to naturally ventilated buildings as shown by the work of Nematchoua and his colleagues in [40], while in air-conditioned buildings in temperate zones, the application of adaptive models is similar to that of Fanger, with a slight energy gain according to the studies of Nicol in [54] and De Dear in [49,55]. From the situations mentioned above, we note that, the limit which appears repeatedly in the majority of the thermal indicator models cited, is the absence of contextual physiological parameters in certain climatic zones. This is the case with skin temperature and heat loss through evaporation of sweat from the surface of the skin for people living in hot and humid climates, especially the area of sub-Saharan Africa (equatorial and humid tropical Africa). Current work uses the default data and leads to lower thermal comfort temperatures than those expected in the field in air-conditioned buildings, as shown by the studies by Kemajou and his colleagues in [37], Olissan and his colleagues in [41], Djongyang and his colleagues in [38], Nematchoua and his colleagues in [40] etc. It is therefore important to seek prediction models for skin temperature and heat loss by evaporation that take into account local climatic specificities. These models will be able to predict more rigorously the thermal comfort indices in air-conditioned buildings (comfort temperature, PMV, PPD) and other thermal indices, then better suited to the populations of the areas concerned. Our research therefore consists in proposing models for predicting skin temperature and heat loss by evaporation for people living in hot and humid climates in sub-Saharan Africa, like the city of Douala in Cameroon where the data has been collected. The measurements will depend on metabolic activity, air speed and relative humidity. The populations tested are people with black skin. A statistical analysis study is carried out on the data collected and a comparison of the models established with those existing.

2. Methodology

2.1. Site presentation

Experiments are conducted in the city of Douala (Economic Capital of Cameroon, Figure 1). Douala is located in the coastal region of Cameroon, along the Atlantic Ocean, between 4°03'N and 9°42'E. Its area is about 210km^2. The climate is of equatorial type with temperatures located between 18°C and 34°C. The outside air is very humid, its relative humidity is located between 90% in rainy season (from June to October) and 80% in the dry season (November to May). These conditions are identical to those of many coastal cities in sub-Saharan Africa.

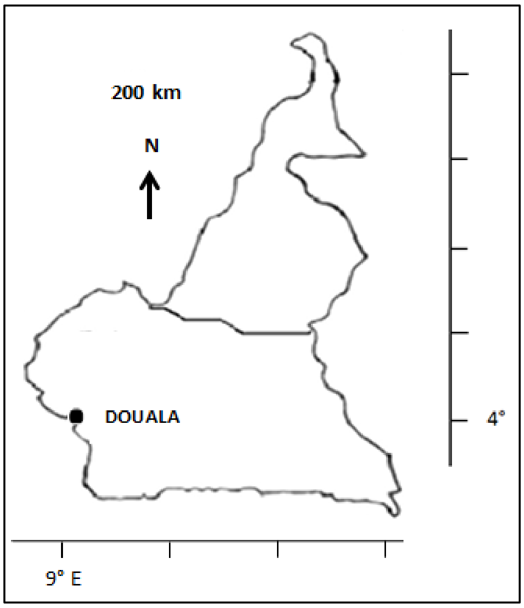

Figure 1: Plan of Cameroon with the indication of the city of Douala

2.2. *Experimental setting*

We worked with a global sample made up of 10 women and 14 men or 24 people, all healthy volunteers. The subjects' professions were diversified, we had teachers, waitresses, industrial agents and workers in commercial spaces. The other mean characteristics of the people were as follows (mean ± standard deviation). For women: age (26.7 ± 3.2 years), weight (68.8 ± 9.4 kg) and size (1.6 ± 0.1 m). For men: age (31.0 ± 6.6 years), weight (71.6 ± 11.4 kg) and size (1.7 ± 0.07 m). Overall: age (29.2 ± 5.7 years), weight (70.4 ± 10.4 kg) and size (1.6 ± 0.1 m). Each of them exercised four levels of metabolic activity in succession (but with a small rest phase). These activities are presented in Table 1. Each activity level was performed at a temperature as close as possible to the temperature of thermal neutrality. Corresponding to the level of metabolic activity considered, as shown in Figure 2, to avoid the risk of sweating felt or feeling cold. The experimental environments were of 2 different types, but responding to similar internal thermal characteristics (Figure 3). In each one, the subjects were in working situations and almost nude, to allow measurements of skin temperatures at all necessary points to be made and to comply with the standard.

Table 1: Levels of metabolic activities selected (modified from ISO 8996 in [56])

Activity level		Ambience category	Metabolic rate
Very light	Reading newspapers, studying	moderate temperature environment	$70W/m^2$ 1.2 met
Light	Slow walking at a spead < 0.9 m/s		$116W/m^2$ 2 met
Moderate	Rapid walk between 0.9 m/s and 1.2 m/s Or walk slowly with a mass of 10kg		$151W/m^2$ 2.6 met
High	Faster walk between 1.2 m/s and 1.9 m/s Or rapid walk with a mass of 10kg		$221W/m^2$ 3.8 met

Note that heavy activities (around 3.8met) could not be done, for two reasons, the heaviness of the activity (heavy activity is not usual for the subjects' daily life) and the feeling cold in the vicinity of the thermo neutrality temperature corresponding to the heavy activity (which moved us away from thermal neutrality).

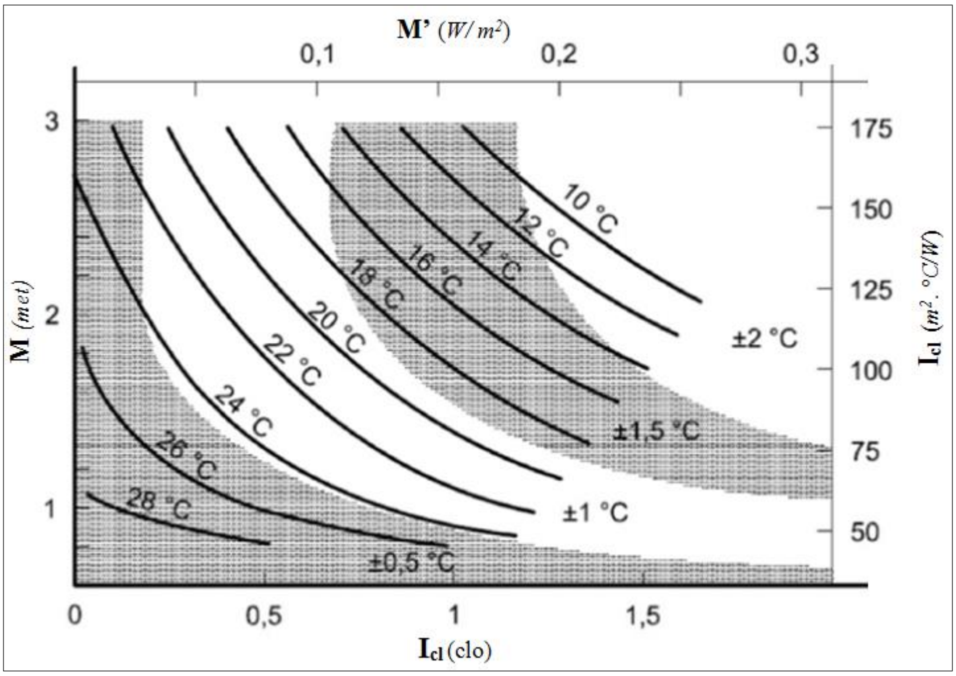

Figure 2: Optimal temperature (modified from ISO 7730 in [26])

M = metabolic rate [W/m^2]; I$_{clo}$ = basic clothing insulation [m^2.°C/W]. The optimum temperature (°C) very close to thermoneutrality is a function of metabolic activity and clothing.

Figure 3: Insight into people in experimental environments

2.3. *Physical and physiological measurements*

Two categories of measurements were made during the work. The first concerns the physical parameters that characterize the thermal environment (ambient temperature, relative humidity, air velocity and radiant temperature). However, the radiant temperature was determined from the correlation of Nagano and his colleagues in [57] presented in equation (1) below. The second category of observations concerns physiological measurements that give the individual's response to thermal environmental conditions in the thermal neutrality zone. This is mainly the skin temperature. The other physiological parameters such as the heat lost by evaporation at the surface of the skin can be obtained from the skin temperature. All the measurements and evaluations carried out comply with the specifications of the standards in force (ISO 7730 and ISO 8996 in [26,56] for metabolic activity, ISO 9920 in [41] for clothing resistance, ISO 9886 in [58] for the evaluation of thermal strain by physiological measurements, and ISO 7726 in [59] for instruments for measuring the physical parameters of the environment). Figure A1 and table A1 in appendix A give a summary of the measuring instruments used and their characteristics.

$$t_r = 0.99 \cdot t_a - 0.01 \qquad R^2 = 0.99 \tag{1}$$

Where t_r = radiant temperature [°C]; t_a = ambient temperature [°C] and R^2 = coefficient of determination.

Skin temperatures are measured at least 15 minutes after the start of work activity, in the vicinity of the corresponding thermal neutrality temperature (Figure 2). Because at this temperature, the regulation of the internal temperature of the body is mainly provided by the vasomotor mechanisms (cutaneous vasodilation and vasoconstriction), there is hardly any sweating felt. According to the ISO 9886 standard in [58], the evaluation of the average skin temperature t_{sk} [°C] can be done with 4, 8 or 14 measurement points (figure 4) depending on the type of thermal environment. For neutral (moderate) or cold thermal environments, 8 or 14 point weightings are recommended, due to the heterogeneity of local skin temperatures. In our study, we opted for the evaluation of this skin temperature with 14 measurement points on each subject (equation 2).

$$t_{sk,14p} = 1/14 \sum_{i=1}^{14} t_i \tag{2}$$

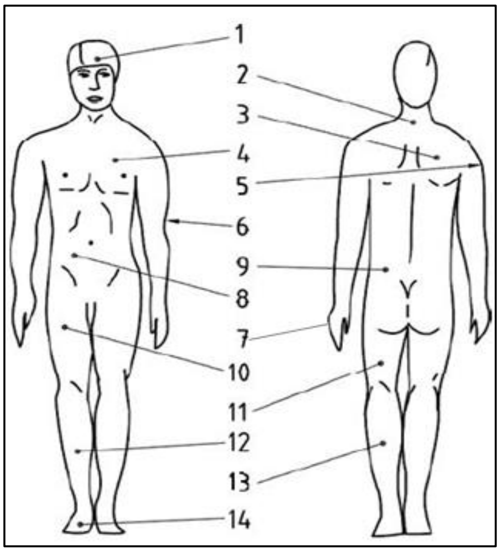

Figure 4: Skin temperature measurement points (modified from ISO 9886 in [58])

1-forehead, 2-neck, 3-right shoulder blade, 4-upper left thorax, 5-right arm in high position, 6-left arm in low position, 7-left hand, 8-right abdomen, 9-para-vertebral zone (kidney) left, 10-right anterior thigh, 11-left posterior thigh, 12-right front tibia, 13-left calf, 14-right instep. During the activity, the ambient temperature (temperature close to the temperature of thermo neutrality relative to the activity) was controlled with the measuring instruments. The average value (between the maximum and the minimum recorded, which was not very far from each other) was used for the activity. The average relative humidity was also calculated against the maximum and minimum measurements observed during the activity; similarly for air velocity.

2.4. Data and processing

We have grouped the measured data into EXCEL files. This made it easier to calculate the averages for each type of data by level of activity (skin temperature of each individual, ambient temperature, air velocity and relative humidity), as well as the averages of ages, sizes and weight for the entire population of our sample. Then we used the graphics functions of EXCEL and MATLAB to analyze the regressions, do the statistical tests and the necessary comparisons. Table B1 in Annex B summarizes the means of all the values measured in the thermal environments and over the entire sample population. A total of 1008 temperature measurement points on the skin were carried out, for all 24 subjects in the population, and for three different types of activities (very light, light and moderate), with ultimately 72 average skin temperatures.

3. Results and discussions

3.1. Regression model of skin temperature as a function of metabolism $t_{sk,d}(M)$

Figure 5 shows a decreasing linear regression of skin temperature as a function of metabolic activity, in the zone of thermal neutrality observed. The coefficient of determination R^2 = 0.749 already provides an acceptable explanation for the variability of skin temperatures as a function of metabolic activity for the individuals in our sample.

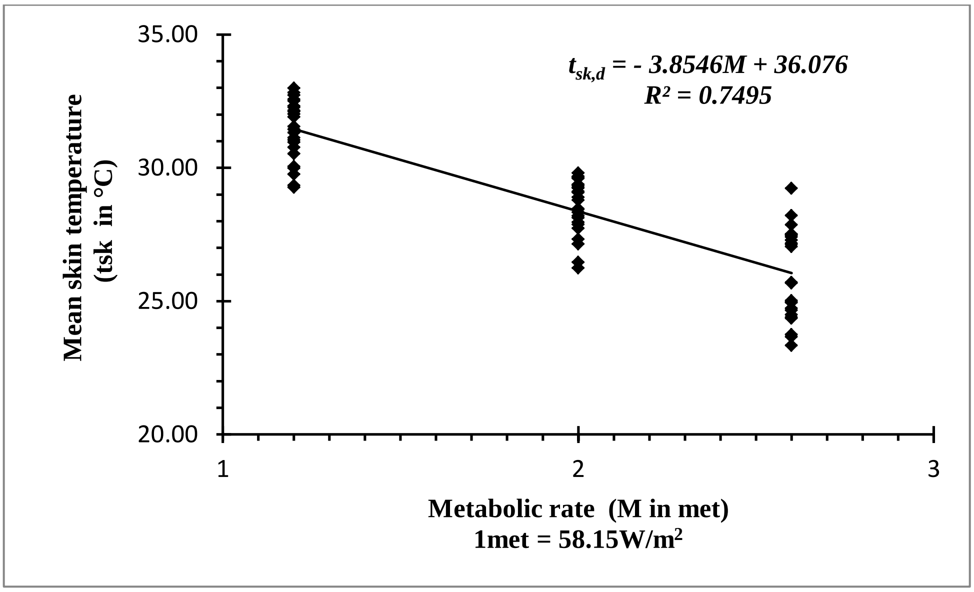

Figure 5: Linear regression model of skin temperature as a function of metabolic activity

Coefficient of determination $R^2 = 0.749$; Adjusted coefficient of determination $R^2_{adj} = 0.745$; residual variance $\sigma^2 = 117.6°C^2$; standard error $\sigma = 1.296°C$.

3.1.1.Validation of the skin temperature regression model and extension to the general population

We validated the determined model using well-known statistical tests presented in numerous statistical inferences such as Dodge and his colleagues in [60], Rakotomalala in [61] etc.

3.1.1.1. Regression global significance test

This involves checking, with a risk of error ($\alpha = 5\%$), whether the regression of coefficient of determination $R^2 = 0.749$ obtained on the sample can reasonably explain the variations in skin temperature with the level of metabolic activity in the general population, where the coefficient of determination is R^2_{pop}.

- Hypothesis H_0: $R^2_{pop} = 0$;
- Unilateral hypothesis H_1: $R^2_{pop} > 0$;
- Statistics of the Fisher-Snedecor test at ($k_1 = 1$) and ($k_2 = n - 2$) degrees of freedom is:

$$F_{obs} = (n-2)\, R^2/1 - R^2 \tag{3}$$

Where n = sample size; R^2 = coefficient of determination;

- Decision rule: we reject H_0 if $F_{obs} > f_{(1-\alpha);\,1;\,(n-2)}$ (Fisher-Snedecor table, table C1 in Appendix C);
- Conclusion ($F_{obs} = 84.73$) and ($f_{(0.95;\,1;\,70)} = 3.98$), the hypothesis H_0 is rejected, so our regression can well explain the relationship between skin temperature and metabolic activity in the general population with a risk of error of 5%.

3.1.1.2. Test on the regression parameters

Recall that, the unilateral Fisher-Snedecor test performed on the coefficient of determination R^2 is equivalent to Student's bilateral test on the coefficient β_1 of the slope of the regression. The next step is to verify whether the relationship between skin temperature and metabolic activity in the overall population admits a constant $\beta_{0,pop}$ which is close to that of the regression in our sample ($\beta_0 = 36.070$ °C) with a risk of error ($\alpha = 5\%$).

- Hypothesis H_0: $\beta_{0,pop} = 0$;
- Bilateral hypothesis H_1: $\beta_{0,\,pop} \neq 0$;
- Student's test statistic at ($k = n - 2$) degrees of freedom:

$$T_{obs} = \left(\beta_0 - \beta_{0,pop}\right)/\sigma\left(\frac{1}{n} + \frac{\bar{M}^2}{(n-1)\sigma^2{}_M}\right)^{1/2} \tag{4}$$

Where n = sample size; M and σ_M are respectively the mean and the standard deviation of the parameter (metabolism rate); σ = standard error on the temperature regression;

- Decision rule: we reject H_0 if $T_{obs} > T_{0\,(1-\alpha/2);\,(n-2)}$ (Student's table, Table D1 in Appendix D);
- Conclusion (T_{obs} = 11.54) > ($T_{0\,(0.975;\,70)}$) = 1.99), the hypothesis H_0 is rejected; the constant of our regression may well explain the relationship between skin temperature and metabolic activity in the general population with a risk of error of 5%.

3.1.1.3. *Confidence interval of parameters*

The aim here is to determine the intervals in which we are 95% sure to find the true values of $\beta_{1,\,pop}$ and $\beta_{0,\,pop}$ which explain the relationship between skin temperature and metabolic activity in the general population.

The statistic for the confidence intervals is as follows:

$$\beta_{0,pop\,(1-\alpha)} \in \left[\beta_0 - T_{(0.975\,;\,70)}\,.\,\sigma\left(\frac{1}{n}+\frac{\bar{M}^2}{(n-1)\sigma^2{}_M}\right)^{1/2} ; \beta_0 + T_{(0.975\,;\,70)}\,.\,\sigma\left(\frac{1}{n}+\frac{\bar{M}^2}{(n-1)\sigma^2{}_M}\right)^{1/2}\right] \quad (5)$$

$$\beta_{1,pop\,(1-\alpha)} \in \left[\beta_1 - T_{(0.975\,;\,70)}\,.\,\sigma\left(\frac{1}{(n-1)\sigma^2{}_M}\right)^{1/2} ; \beta_1 + T_{(0.975\,;\,70)}\,.\,\sigma\left(\frac{1}{(n-1)\sigma^2{}_M}\right)^{1/2}\right] \quad (6)$$

Where n = sample size; M and σ_M = mean and standard deviation on the parameter (metabolism rate); σ = standard error on the temperature regression; $T_{(0.975;\,70)}$ = corresponding parameter in the Student table (Student table, Table D1 in Appendix D);

We determine the following confidence intervals:

$\beta_{0,\,pop,\,95\%}$ ∈ [35.00; 37.13] with a width of 2.13 °C;

$\beta_{1,\,pop,\,95\%}$ ∈ [-4.37; -3.32] with a width of 1.05 ° C/met or

$\beta_{1,\,pop,\,95\%}$ ∈ [-0.0751; -0.0570] with a width of 0.018 °C.m^2/ W.

The small widths of these 95% confidence intervals show, on the one hand, that the regression obtained is very close to the true regression for which it results in only a slight underestimation or overestimation; On the other hand, the risks of sampling errors can also be considered to be reduced.

3.1.1.4. *Residue normality analysis*

We used D'Agostino-Pearson's K2 (K-squared) normality test, based on skewness and kurtosis coefficients to verify the residual normality assumption.

- Hypothesis: the distribution of the residuals is compatible with a normal distribution;
- The test statistic is as follows:

$$\mathrm{K2} = \mathrm{z}_1^2 + \mathrm{z}_2^2 \quad (7)$$

Where z_1 and z_2 are the functions of the test, they asymptotically follow a normal law N(0, 1);

- Decision rule: for a critical threshold ($\alpha = 5\%$), the distribution is compatible with a normal distribution if $K2 < \chi^2_{(1-\alpha)}$ with 2 degrees of freedom (table of χ^2, table E1 of Appendix E);
- Conclusion: ($K2 = 3.83$) and ($\chi^2_{0.95} = 5.99$), the distribution of the residuals is compatible with a normal distribution with a risk of error of 5%.

3.1.1.5. Analysis of homoscedasticity and residue structure

The graphs (figure 6 and figure 7) of the residuals below allow us to make the following observations:

- The mean of the residuals is zero, which shows that the residuals are centered;
- The distribution of residues is homogeneous around the estimated skin temperatures;
- There is no correlation between the residues on the one hand and between the residues and the skin temperature values estimated by the regression on the other hand;
- There is no dependence between residues and metabolic activity.

These remarks lead us to conclude that the residuals have an uncorrelated structure and comply with the homoscedaticity criterion.

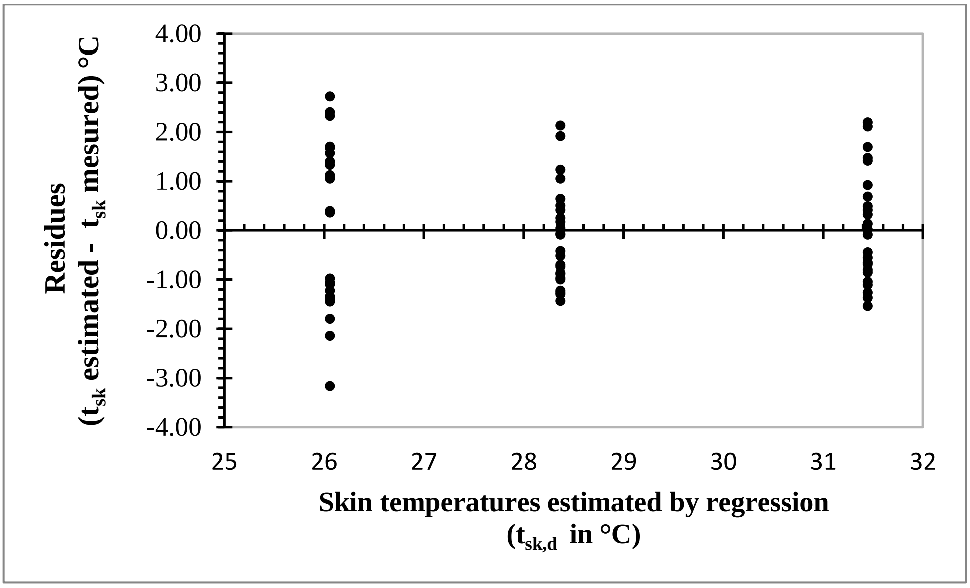

Figure 6: Graph of residues and skin temperatures predicted by the regression

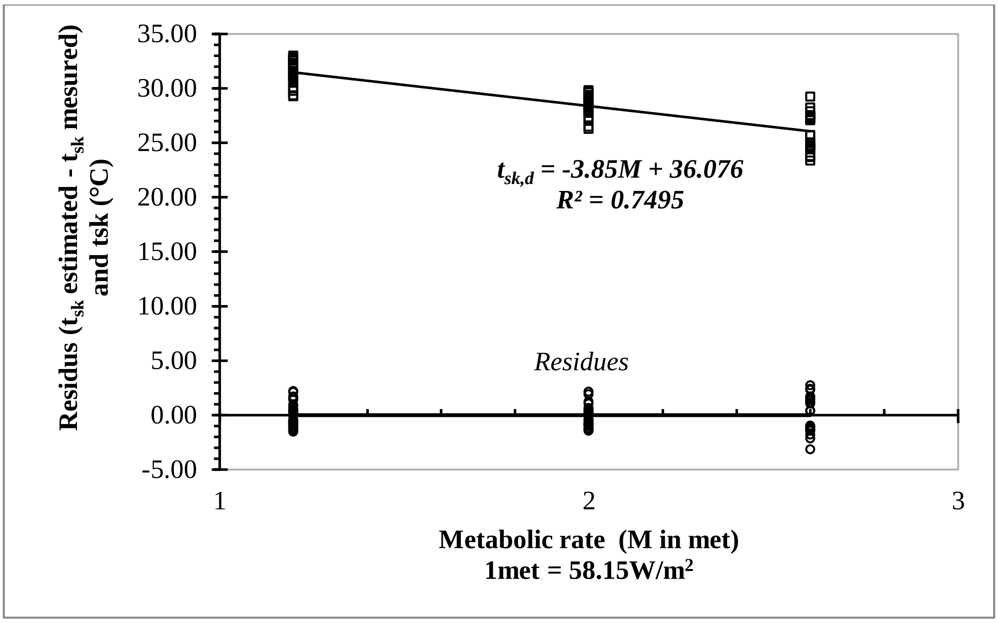

Figure 7: Residue graph, skin temperature regression and metabolism

3.1.1.6. Conclusion on the model validation tests

The statistical tests carried out show that the regression of skin temperatures as a function of the metabolic activity obtained in our sample can be extended to the overall population of the area studied, with a risk of error evaluated at 5%. This model (equation 8, figure 5) is thus considered to be significant for predicting the change in skin temperature (tsk) as a function of metabolic activity (M) in the region.

$$\mathrm{t_{sk,d}} = -0.066 \cdot M + 36.076 \qquad \mathrm{R}^2 = 0.749 \qquad \sigma = 1.296°C \qquad (8)$$

Where: M = net metabolic activity [W/m^2]; $t_{sk,d}$ = predicted skin temperatures [°C]; σ = standard error [°C].

The following section of our work will allow us to establish the difference or equivalence between this model and the standard Fanger model.

3.2. Comparison of the established skin temperature model to the standard Fanger model

3.2.1. Comparison modes

We make here the comparison between the skin temperature model established for the mixed population in the equatorial zone (hot and humid zone), and the Fanger model defined for a mixed population in the temperate zone presented among others in [8,9,10,26], and used by default in hot and humid areas. The comparison will be made on three axes, first the comparison of the slope coefficients of the regressions, then the comparison of the constants of the regressions (Table 2) and finally, the comparison of the prediction errors (figure 8).

Table 2: Comparison of the coefficients and constants of the regressions

Regression	Slope confidence interval	Confidence interval of the constant
Our study (equatorial zone) $\boldsymbol{t_{sk,d} = -0.066 \cdot M + 36.076}$ *	[- 0.0751; - 0.0570]	[35.00; 37.13]
Fanger study (temperate zone) $\boldsymbol{t_{sk,Fanger} = -0.0275 \cdot M + 35.7}$ *	The negative slope (-0.0275) is slightly greater than the confidence interval	The constant (35.7) is included in the confidence interval

* Metabolism rates (M) are expressed in W/m^2 and temperatures (t_{sk}) in °C.

The comparisons made in table 2 show that the constants of the two regressions can be assimilated. However, the fact that the slope coefficient of the Fanger model is slightly excluded from the confidence interval of the slope coefficient of our regression, indicates that the prediction error of the skin temperature in the equatorial zone (hot and humid zone) by Fanger's model will be considerable (figure 8).

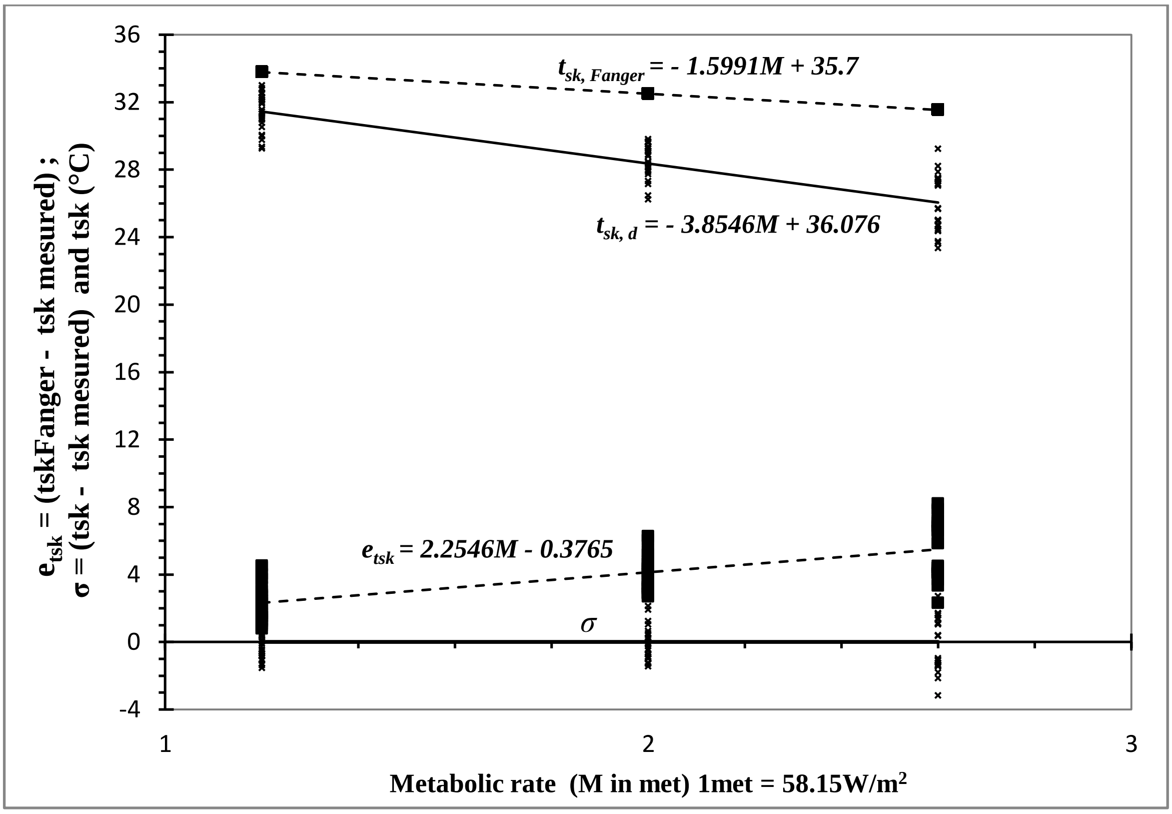

Figure 8: Comparison graph of residues and regressions against metabolism

σ is the standard error on the regression (Figure 5); e_{tsk} is the is the error made by using the standard Fanger model instead of the determined model. Figure 8 actually shows that the error made in using the Fanger model to predict skin temperature in hot and humid areas as a function of metabolic activity is significant. This error has several anomalies including:

- The mean of the residuals is 3.98 °C with a standard deviation of 1.83 °C, which shows a large dispersion of the errors around their mean, for a confidence level of 95%;
- This error grows with increasing metabolic activity and is not dispersed in the same way as the predicted variable (skin temperature).

On the other hand, and as we presented above, the model determined and validated statistically, has residues whose mean is zero, the distribution homogeneous around the estimated skin temperatures, the absence of autocorrelation and the independence with the estimated skin temperatures and metabolic activity.

3.2.2. Conclusion on the comparison of models

Following the statistical validation of the established model and in view of the comparisons made (Table 2, Figure 8), we can conclude that the skin temperature prediction model developed is better suited for the study area. The low slope of this model shows that people living in the equatorial zone (hot and humid zone) have skin with slightly higher thermal inertia. This inertia results in a lower skin temperature for a given metabolic activity under the same ambient conditions. This helps to justify the observation made by authors such as Kemajou and his colleagues in [37], Olissan and his colleagues in [35,36], Djongyang and his colleagues in [38], Nematchoua and his colleagues in [40] in their field studies, that is, people living in hot and humid climates prefer slightly higher thermal comfort temperatures in air-conditioned buildings. We also note that the rate of change in skin temperature as a function of metabolic activity is greater than that of populations in temperate regions. The next section of our study develops a skin temperature prediction model that takes into account the standard Fanger model (temperate zone) and the established model (hot and humid zone) through the difference between the Fanger model and the values observed in the study area.

3.3. Global skin temperature prediction model

From Figure 8 we can write the global expression for the prediction of skin temperature starting from the standard Fanger model and the difference between the predictions made by this model and the values observed in the field. This makes it possible to integrate the local climatic specificities of the equatorial zone (hot and humid region) into the standard model. We thus obtain equation (9).

$$t_{sk,g} = t_{sk,Fanger} - e_{tsk} \pm \sigma \qquad (9) \qquad e_{tsk} = 0.0388 \cdot M - 0.3765$$

$$\sigma = 1.296$$

Where $t_{sk,g}$ [°C] = expression of the global model; $t_{sk,\ Fanger}$ = expression of the Fanger model (as presented in Table 2 and Figure 8 [°C]; e_{tsk} = error made using the standard Fanger model instead of the determined model [°C]; M = metabolic rate [W/m^2]; σ = standard error on the regression established for the determined model

[°C].

3.4. Expressions of heat loss by evaporation at the surface of the skin as a function of skin temperature Esk,d (tsk)

The production and evaporation of sweat (E_{sk}) at the skin level are very low in the thermal neutrality zone, and for a given activity. But when activity increases to produce more heat in the body, additional evaporation of sweat ($E_{r,sw}$) is needed to keep skin temperature in the thermal comfort zone. We will give the expression of skin evaporative exchanges, according to the skin temperature model previously defined (figure 5). The expressions which describe the latent heat exchanges between the skin and the ambient air are repeated in equations (10) and (11) and are also found in the works of authors such as Gagge and his colleagues in [17,18], Candas and his colleagues in [62,63], Johnson and his colleagues in [64], Moujalled and his colleagues in [33], Djongyang and his colleagues in [65], Fohr in [2], ASHRAE Handbook in [3].

$$E_{sk} = E_{diff} + E_{r,sw} = h_{eg} \cdot w \cdot \left(P_{s,sk} - P_a\right) \tag{10}$$

$$w = 0.06 + 0.94 \cdot w_{r,sw} \quad ou \quad w = 0.06 + 0.94\,(E_{r,sw}/E_{max}) \tag{11}$$

Where E_{sk} [W/m^2]; $E_{r,sw}$ [W/m^2]; E_{diff} = heat lost by diffusion of water through de skin layers [W/m^2]; h_{eg} = global coefficient of latent heat exchange at the level of the skin [W/m^{2}kPa]; w = overall skin wettedness [-] (ratio between the evaporation considered $E_{r,sw}$ and the maximum possible evaporation E_{max}); $w_{r,sw}$ = skin wettedness due to sweat evaporation ; 0.06 represents the skin wettedness due to transepidermal diffusion; $P_{s,sk}$ = saturated vapor pressure of water at the surface of the skin [kPa]; P_a = partial pressure of water vapor in air [kPa].

From these equations (10) and (11), we derive the following general terms:

$$E_{diff} = 0.06 \cdot h_{eg}\left(P_{s,sk} - P_a\right) \tag{12}$$

$$E_{r,sw} = 0.94 \cdot w_{r,sw} \cdot h_{eg}\left(P_{s,sk} - P_a\right) \tag{13}$$

Three parameters are to be determined in these relations. The saturated vapor pressure of water at skin temperature $P_{s,sk}(t_{sk})$, the required skin wittedness $w_{r,sw}$ and the global exchange coefficient of heat by evaporation on the surface of the skin h_{eg}. The determination of the saturated vapor pressure of water at the surface of the skin as a function of the skin temperature $P_{s,sk}(t_{sk})$ is obtained by calculating the saturated vapor pressure of water in the boundary layer air, located near the skin. The formula used for this calculation is that of Zürcher and is colleagues in [66].

$$P_{s,sk} = 288.68(1.098 + (t_{sk}/100))^{8.02} \tag{14}$$

Where t_{sk} is the temperature of the boundary layer of air in the vicinity of the skin [°C] and $P_{s,sk}$ the saturated vapor pressure of water at the surface of the skin [Pa]. In order to simplify the terms, we have linearized the above expression (14) in the temperature zone of thermal neutrality studied. The linearization line obtained is presented in figure 9. It shows a linear increase in the saturation vapor pressure with skin temperature, for a considerably high coefficient of determination ($R^2 = 0.99$).

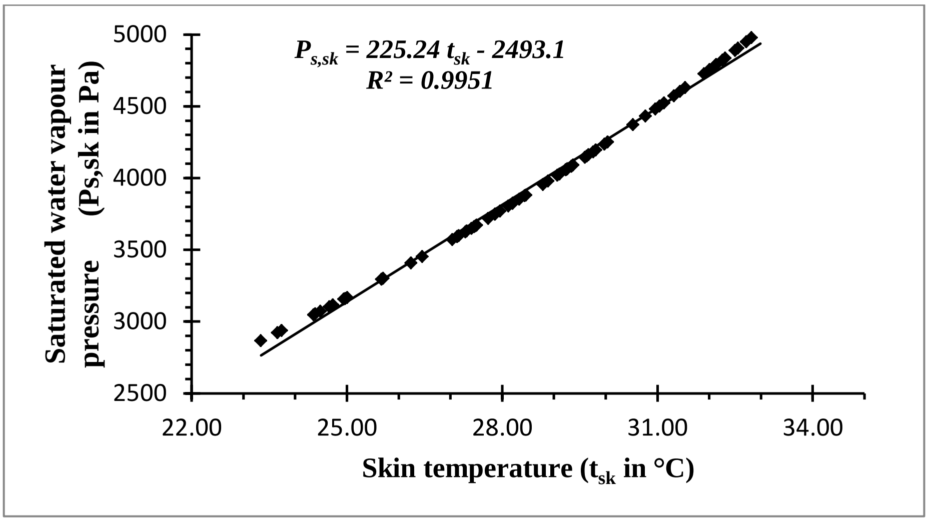

Figure 9: Linear expression of the saturated vapor pressure of water in the boundary layer of air at the surface of the skin

The boundary layer of air on the surface of the skin is considered to be at skin temperature. Regarding the global coefficient of heat exchange by evaporation of water at the surface of the skin (h_{eg}), we see in our case that it only depends on the contact between the nude skin and the air at the velocity v_a. Since the skin is not covered by the clothing (the increase factor of the exchange surface by the clothing is equal to the unit). We thus calculate this coefficient from the following relationships that can be found in the works of Goldman in [67], Olesen and his colleagues in [68,69,70], Oohori and his colleagues in [71], Gagge and his colleagues in [18], Olissan and his colleagues in [35,36], Fohr in [2], ASHRAE Handbook in [3].

$$h_{eg} = \frac{1}{\left(R_{e,cl} + \frac{1}{f_{cl}\ .\ h_{e,a}}\right)}$$

$$R_{e,cl} = \frac{I_{cl}}{L_a . i_{cl}}$$

$f_{cl} = 1.0 + 1.97.I_{cl}$, the skin being nude $I_{cl} = 0\ et\ f_{cl} = 1.0$

$$L_a = h_{e,a}/h_c$$

$$h_c = MAX\left[2.38(t_{sk} - t_a)^{0.25};\ 12.1 \cdot {v_a}^{0.5}\right]$$

$$L_a = 15.15\,(t_{sk} + 273.2)/273.2 \qquad (15)$$

Where: $h_{e,a}$ = latent heat exchange coefficient between skin and air [W/m^2.kPa]; L_a = Lewis factor for water evaporation from the skin surface [K/kPa]; f_{cl} = factor increasing the exchange surface area by the clothing, equal to the unit for nude skin; I_{cl} = basic clothing insulation [m^{2}K/W], equal zero for nude skin; h_c = heat exchange coefficient by convection at the surface of the skin [W/m^2.K]; i_{cl} = permeability of water vapor through the clothing; t_a = ambient air temperature [°C]; v_a = air velocity [m/s]; t_{sk} = skin temperature [°C]. As for the skin wettedness required for comfort ($w_{r,sw}$), it will be calculated by assuming that: “skin wettedness being, by definition, a ratio between the wetted surface required and the total surface area of the body, its variability is almost the same for all populations, regardless of the climatic zone ”. This hypothesis can be accepted for 3 reasons:

- Firstly because skin wettedness is not a direct result of the relative activity of the sweat glands and the evaporative potential of the environment, since the body directly regulates the rate of sweating, the wettedness of the skin strongly reflects the discomfort which is related to the extent of sweat on the skin, according to ASHRAE Handbook in [3] ;
- Second, skin wettdness somewhat expresses the required wetted surface, from which the evaporation of sweat is necessary to overcome an increase in skin temperatures;
- Thirdly, we find the same corpulences of individuals in all climatic zones.

Thus, we will determine the skin wettedness required for comfort by setting the equality between the general expression of equation (13) for $E_{r,sw}$ and the corresponding Fanger expression presented in equation (16), formulations considered in numerous works and books, among others, Fanger in [8, 9, 10], Gagge and his colleagues in [17,18], ISO 7730 in [26], Martinet and his colleagues in [72], ASHRAES tandard55 in [27], ISO 11079 in [30], Moujalled and his colleagues in [33], Djongyang and his colleagues in [64], Fohr in [2], ASHRAE Handbook in [3] etc.

$$E_{r,sw,Fanger} = 0.42\,(M - W - 58.15) \tag{16}$$

$$t_{sk,Fanger} = -0.0275 \cdot M + 35.7$$

$$E_{diff,Fanger} = 3.05 \cdot 10^{-3}\left(256 \cdot t_{sk,Fanger}\ -\ 3373 - P_a\right)$$

$$E_{sk,Fanger} = E_{r,sw,Fanger} + E_{diff,Fanger}$$

Where M = total metabolic rate [W/m^2]; W = metabolic rate used for physical work [W/m^2]; $E_{r,sw,Fanger}$ [W/m^2]. Note that, the usual tables give the net metabolic rate (M) congruent to (M-W) from equation (16), unless otherwise indicated.

The equality between equations (13) and (16) for the terms $E_{r,sw}$ gives us equation (17):

$$w_{r,sw} =\ 0.42\,(M - W - 58.15)/0.94 \cdot\ h_{eg}\left(P_{s,sk} - P_a\right) \tag{17}$$

Ultimately, the calculations carried out over the entire range of our skin temperature data and other corresponding parameters (Table B1, Appendix B) allowed us to obtain the following results:

- Lewis factor mean, L_a = 16.73 K/kPa, with a standard deviation of 0.14;
- Average of the latent heat exchange coefficient between nude skin and air, $h_{e,g}$ = 64.04 W/m^{2}kPa, with a standard deviation of 0.54;
- Linear model for predicting evaporative heat loss at the surface of the skin $E_{sk,d}(P_{s,sk}, P_a, M)$ [W/m^2] obtained by applying equations (12), (13) and (17);

$$E_{diff,d} = 3.84 \cdot 10^{-3}\left(P_{s,sk} - P_a\right) \tag{18}$$

$$E_{r,sw,d} = 0.42\ (M - W - 58.15)$$

With the vapor pressures $P_{s,sk}$ and P_a [Pa] and the metabolism rate M [W/m^2];

- Linear model for predicting heat loss by evaporation at the surface of the skin $E_{sk,d}(P_a, M, t_{sk})$ [W/m^2] obtained by introducing the expression of $P_{s,sk}(t_{sk})$ [Pa] of Figure 9 into equation (18);

$$E_{diff,d} = 3.84 \cdot 10^{-3}\left(225.24 \cdot t_{sk,d} - 2493.1 - P_a\right) \tag{19}$$

$$E_{r,sw,d} = 0.42\ (M - W - 58.15)$$

With vapor pressure P_a [Pa], metabolism rate M [W/m^2] and skin temperature $t_{sk,d}$ [°C];

- Linear model for predicting evaporative heat loss at the surface of the skin $E_{sk,d}(P_a, M)$ [W/m^2] obtained by introducing the expression $t_{sk,d}(M)$ [°C] from the equation (8) in equation (19);

$$E_{diff,d} = 3.84 \cdot 10^{-3}(5632.65 - 14.93 \cdot M - P_a) \tag{20}$$

$$E_{r,sw,d} = 0.42\ (M - W - 58.15)$$

With the vapor pressure Pa [Pa] and the metabolism rate M [W/m^2].

We note that, the linear model of heat loss by skin evaporation that we have established is different from that of Fanger only by the term of the natural diffusion of water vapor through the skin (E_{diff}). This relates two main things:

- The skin of people living in the equatorial zone (hot and humid zone) behaves naturally differently from that of people living in temperate zones. This difference occurs in the diffusion of water vapor through the layers of the skin and is a result of skin temperature;
- The evaporation of sweat from the surface of the skin ($E_{r,sw}$) required to cool it in order to maintain comfort when metabolic activity increases, is the same under the same conditions of activities for individuals in the equatorial zones (hot and humid) and temperate, subject to the reasons justifying our

hypothesis.

3.5. Comparison between the established evaporative heat loss model and the standard Fanger model

We compare in figure 10, the Fanger model of equation (16) corresponding to the prediction of the heat lost by evaporative phenomena at the level of the skin in a temperate zone (applied by default to hot and humid zones) to the model established in this work (hot and humid zone) presented in equations (8) and (19). In this figure (figure 10), we observe a considerable difference between the prediction made by the determined model and that made by the standard Fanger model. The Fanger line is thus above the determined line. Also, the observed difference increases with the increase in metabolic heat production. There is also a difference in the rate of change, which is slightly stronger for the Fanger regression line. Faced with these remarks, we can conclude that the skin of people living in the equatorial zone (hot and humid zone) has:

- A slightly weaker water vapor diffusion flux than that of people living in temperate zones; in other words, the skin of people living in the equatorial zone (hot and humid zone) loses less water by diffusion or insensitive perspiration;
- A slightly higher skin barrier than that of people living in temperate zones.

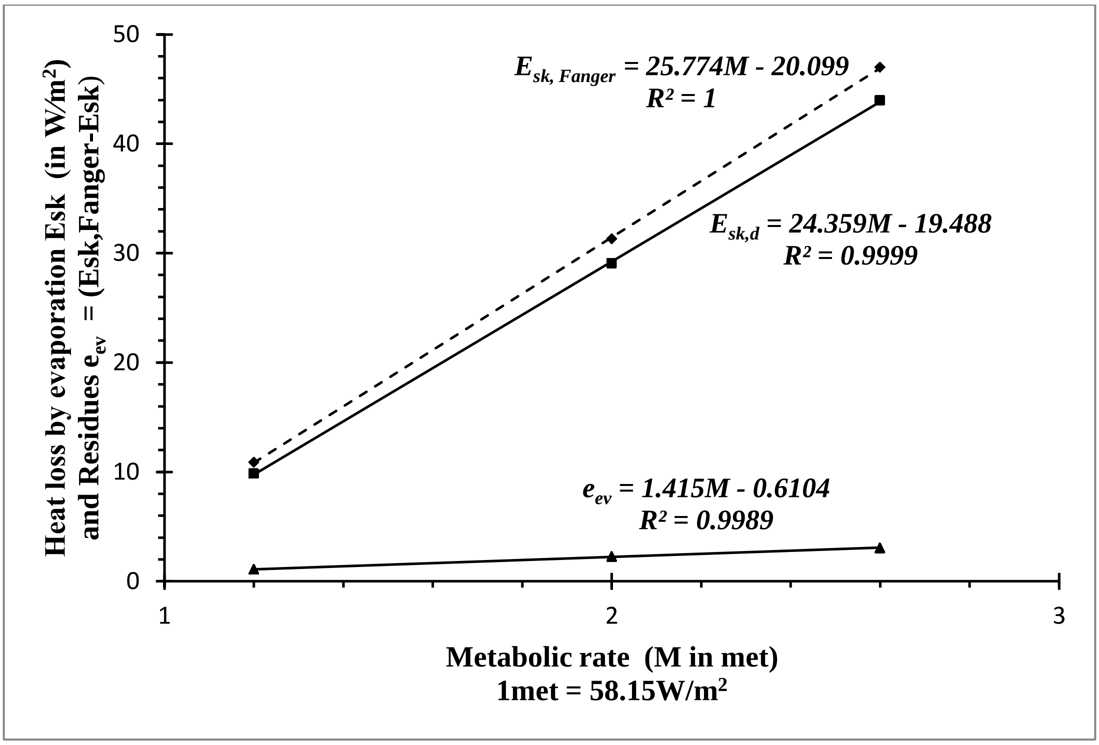

Figure 10: Comparison of evaporative energies as a function of metabolism

e_{ev} is the residual difference between the evaporative energies; $E_{sk,Fanger}$ is regression line corresponding to the Fanger model; $E_{sk,d}$ is regression line corresponding to the determined model.

3.6. Global model of heat loss by skin evaporation

As we did in the case of the skin temperature prediction model, we can also use the deviation observed in figure 10 to write a global model for predicting heat loss by evaporation, which incorporates the particularity of the skin of people in the equatorial zone (hot and humid zone), and thus correct the standard Fanger model integrated in many heat balance calculation software. We thus obtain equation (21):

$$E_{sk,g} = E_{sk,\,Fanger} - e_{ev} \tag{21}$$

$$e_{ev} = 0.0243 \cdot M - 0.6104$$

Where: $E_{sk,g}$ = global model of heat loss by evaporation at the surface of the skin [W/m^2]; $E_{sk,Fanger}$ = Fanger's model for evaporative heat loss at the skin surface from equation (16) [W/m^2]; e_{ev} = residual difference between the evaporative heats (figure 10) [W/m^2]. Note that the metabolic rate (M to met) in Figure 10 is converted to W/m^2 in equation (21).

3.7. Summary of the main results

Table 3: Summary of the main results

Nature of the Model	Climatic origin of the model		
	Temperate zone Fanger model ($t_{sk\ Fanger}$)	Hot and Humid zone Determined model ($_{tsk,d}$)	Temperate zone and Hot and Humid zone Corrective model
Skin temperature	$t_{sk,Fanger} = -0.0275 \cdot M + 35.7$	$t_{sk,d} = -0.066 \cdot M + 36.076$ $R^2 = 0.749$ $\sigma = 1.296$	$t_{sk,g} = t_{sk,Fanger} - e_{tsk} \pm \sigma$ $e_{tsk} = 0.0388 \cdot M - 0.3765$
Heat loss by evaporation	$E_{r,sw,Fanger} = 0.42\,(M - W - 58.15)$ $E_{diff,Fanger} = 3.05 \cdot 10^{-3}\big(256.\,t_{sk,Fanger} - 3373 - P_a\big)$ $E_{sk,Fanger} = E_{r,sw,Fanger} + E_{diff,Fanger}$	$E_{r,sw,d} = 0.42\,(M - W - 58.15)$ $E_{diff,d} = 3.84 \cdot 10^{-3}\big(225.24 \cdot t_{sk,d} - 2493.1 - P_a\big)$	$E_{sk,g} = E_{sk,\,Fanger} - e_{ev}$ $e_{ev} = 0.0243 \cdot M - 0.6104$
Other determined mean values		Lewis factor, L_a = 16.73 K/kPa Standard deviation = 0.14 Global coefficient of latent heat exchange between nude skin and air, $h_{e,g}$ = 64.04 W/m^{2}kPa) Standard deviation = 0.54	

Table 3 gives a brief summary of the results obtained, the nature and climatic origin of the existing models as well as those that we have determined.

σ is the standard error on the regression (figure 5); e_{tsk} and e_{ev} are errors made by using the standard Fanger model instead of the determined model (equations 8, 9, 16, 19, 21; figures 8 and 10).

4. Conclusion

At the end of our study, which consisted in establishing models for predicting skin temperature and heat loss by evaporation (depending on metabolic activity) for thermal comfort in hot and humid areas and particularly in Cameroon, we can basically remember that:

- A skin temperature prediction model has been established and validated, it presents a considerable difference compared to the standard Fanger model developed in temperate zones, and used by default for local studies;
- A global skin temperature prediction model, which integrates the particularity of the studied climatic zone (hot and humid zone) in the Fanger model, was determined taking into account the observed deviation, for corrections in existing software;
- A model for predicting heat loss by evaporation was also established, it also presents a considerable difference compared to the standard Fanger model developed in temperate zones;
- Likewise, a global model for predicting heat loss by evaporation, which integrates the particularity of the climatic zone studied (hot and humid zone) in the standard Fanger model, was determined taking into account the observed deviation.

It emerges from our interpretations that the skin of the populations of the hot and humid zone and particularly in Douala in Cameroon, has:

- A slightly higher thermal inertia than that of populations in temperate climatic zones; this thermal inertia is manifested by a low skin temperature compared to the metabolic activity; this helps to justify the observation made by authors such as Kemajou and his colleagues in [37], Olissan and his colleagues in [35,36], Nematchoua and his colleagues in [40], Djongyang and his colleagues in [38] in their field studies, that is, people living in the hot and humid climate prefer slightly higher thermal comfort temperatures in air-conditioned buildings; We also note a high rate of change in skin temperature as a function of the rate of metabolism under the same ambient conditions;
- A skin barrier slightly higher than that of populations in temperate climatic zones; this skin barrier is manifested by a weak diffusion of water vapor through the skin layers or a weak insensitive perspiration; in addition, there is a low rate of change in heat loss by transepidermal diffusion as a function of the rate of metabolism under the same ambient conditions.

Thus in hot and humid climatic regions (particularly for people with black skin), the above models are elements that will allow us to better define the thermal comfort conditions in air-conditioned buildings through the PMV and PDD comfort indices, but also working conditions in cold spaces through the IREQ index. However, one can wonder if the characteristic mentioned above, for the skin of people living in the studied climatic zone is innate (natural) or if it can be acquired by an adaptation to the climate.

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Appendix A

Table A1: Characteristics of the instruments and measuring means used

Measure categories	Parameters to be measured	Measuring instruments and main characteristics	Quantities
Physical measurements	Temperature (° C) and Relative humidity (%) of the room air	Thermocouple thermometer -10 ° C to 400 ° C; response time 1s resolution 0.1. accuracy ± 1 ° c	01
		Thermo hygrometer (RoHS) T: -50 ° C to 70 ° C; response time 10s resolution 0.1; accuracy ± 1 ° c RH: 10% to 99%; response time 10s resolution 1%; accuracy 3% (50% to 80%)	01
	Air velocity (m / s)	Air-fliow anemometer (SMART SENSOR AR 826+)	01
		Hot wire thermo anemometer (SMART SENSOR AR 866)	01
	Clothing insulation (clo)	Standard ISO 9920	
Physiological measurements	skin temperature (°C)	Infrared thermometer (TOTAL) -30 ° C to 550 ° C; response time 1s 630 to 670nm; accuracy ± 0.1 ° C.	01
	Metabolic rate (met or W/m^2)	Standard ISO 8996	

Figure A1: Measuring instruments used

Appendix B

Table B1: Summary of measures

A	**F**	**H**	**Ambience parameters**				**A**	**F**	**H**	**Ambience parameters**			
(met)	$\overline{t_{sk}}$ (°C)	$\overline{t_{sk}}$ (°C)	$\overline{t_a}$ (°C)	$\overline{t_r}$ (°C)	$\overline{HR_a}$ (%)	$\overline{v_a}$ (m/s)	(met)	$\overline{t_{sk}}$ (°C)	$\overline{t_{sk}}$ (°C)	$\overline{t_a}$ (°C)	$\overline{t_r}$ (°C)	$\overline{HR_a}$ (%)	$\overline{v_a}$ (m/s)
1,2	31,13	29,34	28	27,7	87,5	0,1	2	28,89	26,24	25,5	25,2	82,5	0,1
	30,96	29,26						28,79	26,46				
	31,32	30,04						29,24	27,14				
	31,04	29,76						29,34	27,32				
	32,11	30,53						29,26	27,73				
	32,14	30,77						29,81	27,87				
	29,98	32,01						28,46	29,07				
	32,82	32,72						27,96	28,33				
	32,31	32,99						29,11	28,44				
	31,90	32,56						29,37	28,20				
		31,54							28,12				
		32,26							29,64				
		31,44							29,67				
		32,50							29,60				

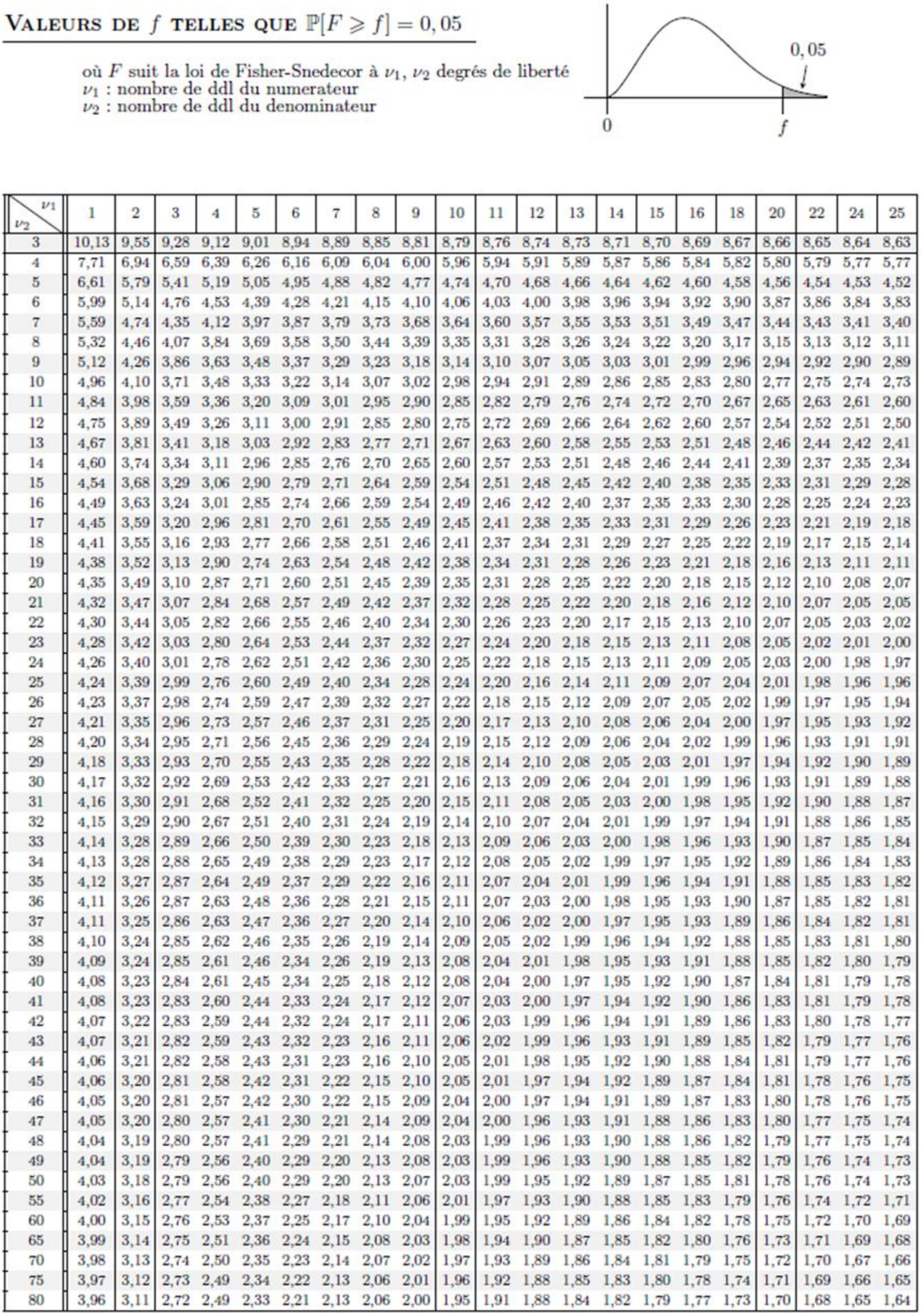
A (met)	**F** $\overline{t_{sk}}$ (°C)	**H** $\overline{t_{sk}}$ (°C)	$\overline{t_a}$ (°C)	$\overline{t_r}$ (°C)	$\overline{HR_a}$ (%)	$\overline{v_a}$ (m/s)
2,6	25,67	23,34	24,5	24,2	68,5	0,1
	25,01	23,66				
	27,16	24,66				
	29,23	24,49				
	27,86	24,73				
	27,46	24,97				
	27,13	25,70				
	27,51	24,36				
	27,41	24,39				
	27,04	24,94				
		23,74				
		27,49				
		27,29				
		28,21				

Other subject parameters							
Men				**Men and women**			
$\overline{I_{clo}}$ (clo)	$\overline{age}$ (years)	$\overline{weigt}$ (kg)	$\overline{size}$ (m)	$\overline{I_{clo}}$ (clo)	$\overline{age}$ (years)	$\overline{weight}$ (kg)	$\overline{size}$ (m)
< 0,0*	31,0 ±6,6	71,6 ±11,4	1,7 ±0,07	< 0,0	29,2 ±5,7	70,4 ±10,4	1,6 ±0,1
Women							
$\overline{I_{clo}}$ (clo)	$\overline{age}$ (years)	$\overline{weight}$ (kg)	$\overline{size}$ (m)				
< 0,0*	26,7 ±3,2	68,8 ±9,4	1,6 ±0,1				

A = metabolic activity; H = men; F = women; I_{clo} =clothing insulation; t_r = mean radiant temperature [° C]; t_a = average ambient temperature [° C]; HR_a = average relative humidity [%]; v_a = average ambient air velocity [m/s]; t_{sk} = mean skin temperature for for each individual [°C]; Iclo = clothing insulation [clo]. * Subjects are almost nude, only private parts are covered by underwear;

Appendix C

Table C1: Fisher-Snedecor table



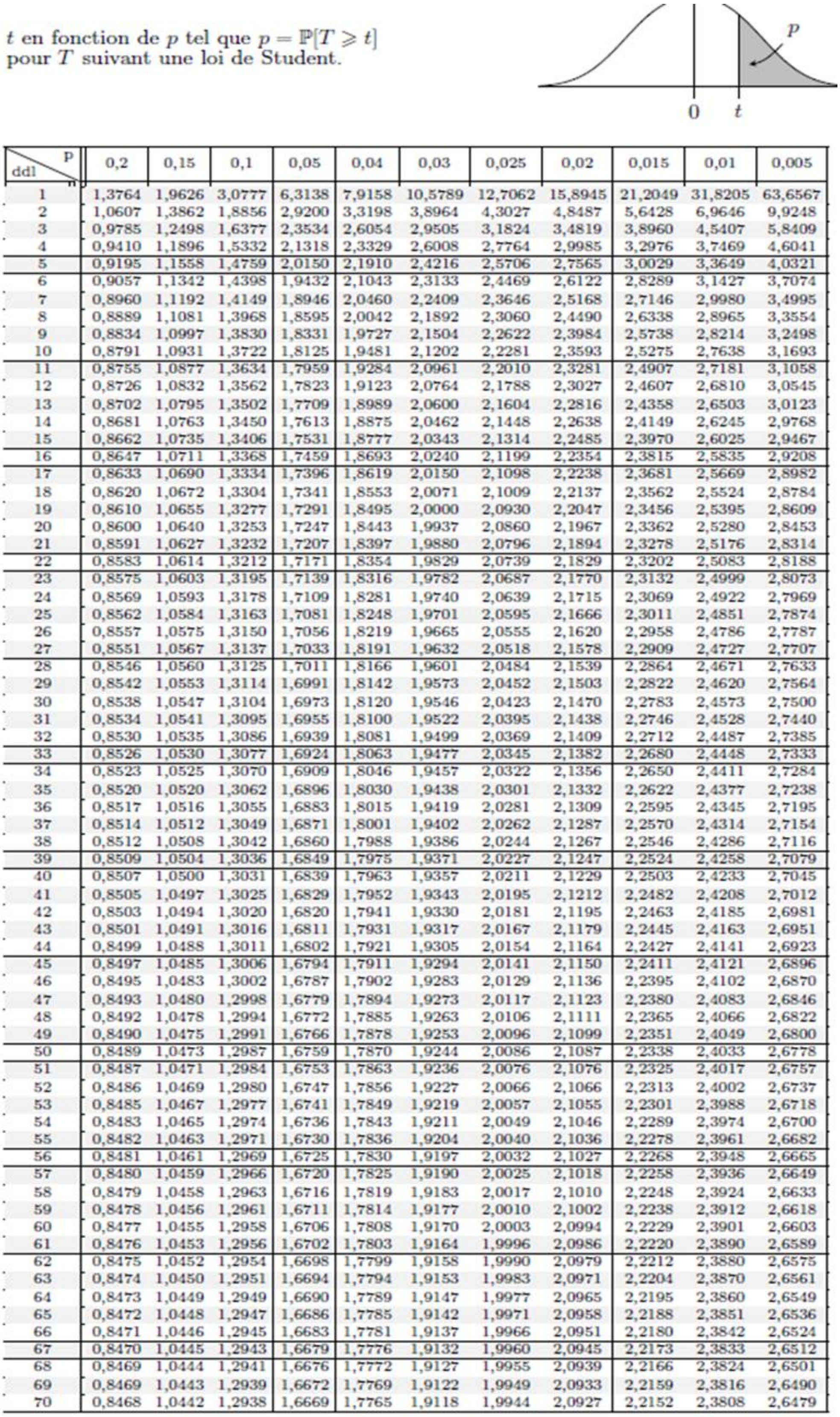
VALEURS DE f TELLES QUE $\mathbb{P}[F \geqslant f] = 0,05$

où F suit la loi de Fisher-Snedecor à ν_1, ν_2 degrés de liberté
ν_1 : nombre de ddl du numerateur
ν_2 : nombre de ddl du denominateur

ν_1 ν_2	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	18	20	22	24	25
3	10,13	9,55	9,28	9,12	9,01	8,94	8,89	8,85	8,81	8,79	8,76	8,74	8,73	8,71	8,70	8,69	8,67	8,66	8,65	8,64	8,63
4	7,71	6,94	6,59	6,39	6,26	6,16	6,09	6,04	6,00	5,96	5,94	5,91	5,89	5,87	5,86	5,84	5,82	5,80	5,79	5,77	5,77
5	6,61	5,79	5,41	5,19	5,05	4,95	4,88	4,82	4,77	4,74	4,70	4,68	4,66	4,64	4,62	4,60	4,58	4,56	4,54	4,53	4,52
6	5,99	5,14	4,76	4,53	4,39	4,28	4,21	4,15	4,10	4,06	4,03	4,00	3,98	3,96	3,94	3,92	3,90	3,87	3,86	3,84	3,83
7	5,59	4,74	4,35	4,12	3,97	3,87	3,79	3,73	3,68	3,64	3,60	3,57	3,55	3,53	3,51	3,49	3,47	3,44	3,43	3,41	3,40
8	5,32	4,46	4,07	3,84	3,69	3,58	3,50	3,44	3,39	3,35	3,31	3,28	3,26	3,24	3,22	3,20	3,17	3,15	3,13	3,12	3,11
9	5,12	4,26	3,86	3,63	3,48	3,37	3,29	3,23	3,18	3,14	3,10	3,07	3,05	3,03	3,01	2,99	2,96	2,94	2,92	2,90	2,89
10	4,96	4,10	3,71	3,48	3,33	3,22	3,14	3,07	3,02	2,98	2,94	2,91	2,89	2,86	2,85	2,83	2,80	2,77	2,75	2,74	2,73
11	4,84	3,98	3,59	3,36	3,20	3,09	3,01	2,95	2,90	2,85	2,82	2,79	2,76	2,74	2,72	2,70	2,67	2,65	2,63	2,61	2,60
12	4,75	3,89	3,49	3,26	3,11	3,00	2,91	2,85	2,80	2,75	2,72	2,69	2,66	2,64	2,62	2,60	2,57	2,54	2,52	2,51	2,50
13	4,67	3,81	3,41	3,18	3,03	2,92	2,83	2,77	2,71	2,67	2,63	2,60	2,58	2,55	2,53	2,51	2,48	2,46	2,44	2,42	2,41
14	4,60	3,74	3,34	3,11	2,96	2,85	2,76	2,70	2,65	2,60	2,57	2,53	2,51	2,48	2,46	2,44	2,41	2,39	2,37	2,35	2,34
15	4,54	3,68	3,29	3,06	2,90	2,79	2,71	2,64	2,59	2,54	2,51	2,48	2,45	2,42	2,40	2,38	2,35	2,33	2,31	2,29	2,28
16	4,49	3,63	3,24	3,01	2,85	2,74	2,66	2,59	2,54	2,49	2,46	2,42	2,40	2,37	2,35	2,33	2,30	2,28	2,25	2,24	2,23
17	4,45	3,59	3,20	2,96	2,81	2,70	2,61	2,55	2,49	2,45	2,41	2,38	2,35	2,33	2,31	2,29	2,26	2,23	2,21	2,19	2,18
18	4,41	3,55	3,16	2,93	2,77	2,66	2,58	2,51	2,46	2,41	2,37	2,34	2,31	2,29	2,27	2,25	2,22	2,19	2,17	2,15	2,14
19	4,38	3,52	3,13	2,90	2,74	2,63	2,54	2,48	2,42	2,38	2,34	2,31	2,28	2,26	2,23	2,21	2,18	2,16	2,13	2,11	2,11
20	4,35	3,49	3,10	2,87	2,71	2,60	2,51	2,45	2,39	2,35	2,31	2,28	2,25	2,22	2,20	2,18	2,15	2,12	2,10	2,08	2,07
21	4,32	3,47	3,07	2,84	2,68	2,57	2,49	2,42	2,37	2,32	2,28	2,25	2,22	2,20	2,18	2,16	2,12	2,10	2,07	2,05	2,05
22	4,30	3,44	3,05	2,82	2,66	2,55	2,46	2,40	2,34	2,30	2,26	2,23	2,20	2,17	2,15	2,13	2,10	2,07	2,05	2,03	2,02
23	4,28	3,42	3,03	2,80	2,64	2,53	2,44	2,37	2,32	2,27	2,24	2,20	2,18	2,15	2,13	2,11	2,08	2,05	2,02	2,01	2,00
24	4,26	3,40	3,01	2,78	2,62	2,51	2,42	2,36	2,30	2,25	2,22	2,18	2,15	2,13	2,11	2,09	2,05	2,03	2,00	1,98	1,97
25	4,24	3,39	2,99	2,76	2,60	2,49	2,40	2,34	2,28	2,24	2,20	2,16	2,14	2,11	2,09	2,07	2,04	2,01	1,98	1,96	1,96
26	4,23	3,37	2,98	2,74	2,59	2,47	2,39	2,32	2,27	2,22	2,18	2,15	2,12	2,09	2,07	2,05	2,02	1,99	1,97	1,95	1,94
27	4,21	3,35	2,96	2,73	2,57	2,46	2,37	2,31	2,25	2,20	2,17	2,13	2,10	2,08	2,06	2,04	2,00	1,97	1,95	1,93	1,92
28	4,20	3,34	2,95	2,71	2,56	2,45	2,36	2,29	2,24	2,19	2,15	2,12	2,09	2,06	2,04	2,02	1,99	1,96	1,93	1,91	1,91
29	4,18	3,33	2,93	2,70	2,55	2,43	2,35	2,28	2,22	2,18	2,14	2,10	2,08	2,05	2,03	2,01	1,97	1,94	1,92	1,90	1,89
30	4,17	3,32	2,92	2,69	2,53	2,42	2,33	2,27	2,21	2,16	2,13	2,09	2,06	2,04	2,01	1,99	1,96	1,93	1,91	1,89	1,88
31	4,16	3,30	2,91	2,68	2,52	2,41	2,32	2,25	2,20	2,15	2,11	2,08	2,05	2,03	2,00	1,98	1,95	1,92	1,90	1,88	1,87
32	4,15	3,29	2,90	2,67	2,51	2,40	2,31	2,24	2,19	2,14	2,10	2,07	2,04	2,01	1,99	1,97	1,94	1,91	1,88	1,86	1,85
33	4,14	3,28	2,89	2,66	2,50	2,39	2,30	2,23	2,18	2,13	2,09	2,06	2,03	2,00	1,98	1,96	1,93	1,90	1,87	1,85	1,84
34	4,13	3,28	2,88	2,65	2,49	2,38	2,29	2,23	2,17	2,12	2,08	2,05	2,02	1,99	1,97	1,95	1,92	1,89	1,86	1,84	1,83
35	4,12	3,27	2,87	2,64	2,49	2,37	2,29	2,22	2,16	2,11	2,07	2,04	2,01	1,99	1,96	1,94	1,91	1,88	1,85	1,83	1,82
36	4,11	3,26	2,87	2,63	2,48	2,36	2,28	2,21	2,15	2,11	2,07	2,03	2,00	1,98	1,95	1,93	1,90	1,87	1,85	1,82	1,81
37	4,11	3,25	2,86	2,63	2,47	2,36	2,27	2,20	2,14	2,10	2,06	2,02	2,00	1,97	1,95	1,93	1,89	1,86	1,84	1,82	1,81
38	4,10	3,24	2,85	2,62	2,46	2,35	2,26	2,19	2,14	2,09	2,05	2,02	1,99	1,96	1,94	1,92	1,88	1,85	1,83	1,81	1,80
39	4,09	3,24	2,85	2,61	2,46	2,34	2,26	2,19	2,13	2,08	2,04	2,01	1,98	1,95	1,93	1,91	1,88	1,85	1,82	1,80	1,79
40	4,08	3,23	2,84	2,61	2,45	2,34	2,25	2,18	2,12	2,08	2,04	2,00	1,97	1,95	1,92	1,90	1,87	1,84	1,81	1,79	1,78
41	4,08	3,23	2,83	2,60	2,44	2,33	2,24	2,17	2,12	2,07	2,03	2,00	1,97	1,94	1,92	1,90	1,86	1,83	1,81	1,79	1,78
42	4,07	3,22	2,83	2,59	2,44	2,32	2,24	2,17	2,11	2,06	2,03	1,99	1,96	1,94	1,91	1,89	1,86	1,83	1,80	1,78	1,77
43	4,07	3,21	2,82	2,59	2,43	2,32	2,23	2,16	2,11	2,06	2,02	1,99	1,96	1,93	1,91	1,89	1,85	1,82	1,79	1,77	1,76
44	4,06	3,21	2,82	2,58	2,43	2,31	2,23	2,16	2,10	2,05	2,01	1,98	1,95	1,92	1,90	1,88	1,84	1,81	1,79	1,77	1,76
45	4,06	3,20	2,81	2,58	2,42	2,31	2,22	2,15	2,10	2,05	2,01	1,97	1,94	1,92	1,89	1,87	1,84	1,81	1,78	1,76	1,75
46	4,05	3,20	2,81	2,57	2,42	2,30	2,22	2,15	2,09	2,04	2,00	1,97	1,94	1,91	1,89	1,87	1,83	1,80	1,78	1,76	1,75
47	4,05	3,20	2,80	2,57	2,41	2,30	2,21	2,14	2,09	2,04	2,00	1,96	1,93	1,91	1,88	1,86	1,83	1,80	1,77	1,75	1,74
48	4,04	3,19	2,80	2,57	2,41	2,29	2,21	2,14	2,08	2,03	1,99	1,96	1,93	1,90	1,88	1,86	1,82	1,79	1,77	1,75	1,74
49	4,04	3,19	2,79	2,56	2,40	2,29	2,20	2,13	2,08	2,03	1,99	1,96	1,93	1,90	1,88	1,85	1,82	1,79	1,76	1,74	1,73
50	4,03	3,18	2,79	2,56	2,40	2,29	2,20	2,13	2,07	2,03	1,99	1,95	1,92	1,89	1,87	1,85	1,81	1,78	1,76	1,74	1,73
55	4,02	3,16	2,77	2,54	2,38	2,27	2,18	2,11	2,06	2,01	1,97	1,93	1,90	1,88	1,85	1,83	1,79	1,76	1,74	1,72	1,71
60	4,00	3,15	2,76	2,53	2,37	2,25	2,17	2,10	2,04	1,99	1,95	1,92	1,89	1,86	1,84	1,82	1,78	1,75	1,72	1,70	1,69
65	3,99	3,14	2,75	2,51	2,36	2,24	2,15	2,08	2,03	1,98	1,94	1,90	1,87	1,85	1,82	1,80	1,76	1,73	1,71	1,69	1,68
70	3,98	3,13	2,74	2,50	2,35	2,23	2,14	2,07	2,02	1,97	1,93	1,89	1,86	1,84	1,81	1,79	1,75	1,72	1,70	1,67	1,66
75	3,97	3,12	2,73	2,49	2,34	2,22	2,13	2,06	2,01	1,96	1,92	1,88	1,85	1,83	1,80	1,78	1,74	1,71	1,69	1,66	1,65
80	3,96	3,11	2,72	2,49	2,33	2,21	2,13	2,06	2,00	1,95	1,91	1,88	1,84	1,82	1,79	1,77	1,73	1,70	1,68	1,65	1,64

Appendix D

Table D1: Student table



t en fonction de p tel que $p = \mathbb{P}[T \geqslant t]$
pour T suivant une loi de Student.

p ddl	0,2	0,15	0,1	0,05	0,04	0,03	0,025	0,02	0,015	0,01	0,005
1	1,3764	1,9626	3,0777	6,3138	7,9158	10,5789	12,7062	15,8945	21,2049	31,8205	63,6567
2	1,0607	1,3862	1,8856	2,9200	3,3198	3,8964	4,3027	4,8487	5,6428	6,9646	9,9248
3	0,9785	1,2498	1,6377	2,3534	2,6054	2,9505	3,1824	3,4819	3,8960	4,5407	5,8409
4	0,9410	1,1896	1,5332	2,1318	2,3329	2,6008	2,7764	2,9985	3,2976	3,7469	4,6041
5	0,9195	1,1558	1,4759	2,0150	2,1910	2,4216	2,5706	2,7565	3,0029	3,3649	4,0321
6	0,9057	1,1342	1,4398	1,9432	2,1043	2,3133	2,4469	2,6122	2,8289	3,1427	3,7074
7	0,8960	1,1192	1,4149	1,8946	2,0460	2,2409	2,3646	2,5168	2,7146	2,9980	3,4995
8	0,8889	1,1081	1,3968	1,8595	2,0042	2,1892	2,3060	2,4490	2,6338	2,8965	3,3554
9	0,8834	1,0997	1,3830	1,8331	1,9727	2,1504	2,2622	2,3984	2,5738	2,8214	3,2498
10	0,8791	1,0931	1,3722	1,8125	1,9481	2,1202	2,2281	2,3593	2,5275	2,7638	3,1693
11	0,8755	1,0877	1,3634	1,7959	1,9284	2,0961	2,2010	2,3281	2,4907	2,7181	3,1058
12	0,8726	1,0832	1,3562	1,7823	1,9123	2,0764	2,1788	2,3027	2,4607	2,6810	3,0545
13	0,8702	1,0795	1,3502	1,7709	1,8989	2,0600	2,1604	2,2816	2,4358	2,6503	3,0123
14	0,8681	1,0763	1,3450	1,7613	1,8875	2,0462	2,1448	2,2638	2,4149	2,6245	2,9768
15	0,8662	1,0735	1,3406	1,7531	1,8777	2,0343	2,1314	2,2485	2,3970	2,6025	2,9467
16	0,8647	1,0711	1,3368	1,7459	1,8693	2,0240	2,1199	2,2354	2,3815	2,5835	2,9208
17	0,8633	1,0690	1,3334	1,7396	1,8619	2,0150	2,1098	2,2238	2,3681	2,5669	2,8982
18	0,8620	1,0672	1,3304	1,7341	1,8553	2,0071	2,1009	2,2137	2,3562	2,5524	2,8784
19	0,8610	1,0655	1,3277	1,7291	1,8495	2,0000	2,0930	2,2047	2,3456	2,5395	2,8609
20	0,8600	1,0640	1,3253	1,7247	1,8443	1,9937	2,0860	2,1967	2,3362	2,5280	2,8453
21	0,8591	1,0627	1,3232	1,7207	1,8397	1,9880	2,0796	2,1894	2,3278	2,5176	2,8314
22	0,8583	1,0614	1,3212	1,7171	1,8354	1,9829	2,0739	2,1829	2,3202	2,5083	2,8188
23	0,8575	1,0603	1,3195	1,7139	1,8316	1,9782	2,0687	2,1770	2,3132	2,4999	2,8073
24	0,8569	1,0593	1,3178	1,7109	1,8281	1,9740	2,0639	2,1715	2,3069	2,4922	2,7969
25	0,8562	1,0584	1,3163	1,7081	1,8248	1,9701	2,0595	2,1666	2,3011	2,4851	2,7874
26	0,8557	1,0575	1,3150	1,7056	1,8219	1,9665	2,0555	2,1620	2,2958	2,4786	2,7787
27	0,8551	1,0567	1,3137	1,7033	1,8191	1,9632	2,0518	2,1578	2,2909	2,4727	2,7707
28	0,8546	1,0560	1,3125	1,7011	1,8166	1,9601	2,0484	2,1539	2,2864	2,4671	2,7633
29	0,8542	1,0553	1,3114	1,6991	1,8142	1,9573	2,0452	2,1503	2,2822	2,4620	2,7564
30	0,8538	1,0547	1,3104	1,6973	1,8120	1,9546	2,0423	2,1470	2,2783	2,4573	2,7500
31	0,8534	1,0541	1,3095	1,6955	1,8100	1,9522	2,0395	2,1438	2,2746	2,4528	2,7440
32	0,8530	1,0535	1,3086	1,6939	1,8081	1,9499	2,0369	2,1409	2,2712	2,4487	2,7385
33	0,8526	1,0530	1,3077	1,6924	1,8063	1,9477	2,0345	2,1382	2,2680	2,4448	2,7333
34	0,8523	1,0525	1,3070	1,6909	1,8046	1,9457	2,0322	2,1356	2,2650	2,4411	2,7284
35	0,8520	1,0520	1,3062	1,6896	1,8030	1,9438	2,0301	2,1332	2,2622	2,4377	2,7238
36	0,8517	1,0516	1,3055	1,6883	1,8015	1,9419	2,0281	2,1309	2,2595	2,4345	2,7195
37	0,8514	1,0512	1,3049	1,6871	1,8001	1,9402	2,0262	2,1287	2,2570	2,4314	2,7154
38	0,8512	1,0508	1,3042	1,6860	1,7988	1,9386	2,0244	2,1267	2,2546	2,4286	2,7116
39	0,8509	1,0504	1,3036	1,6849	1,7975	1,9371	2,0227	2,1247	2,2524	2,4258	2,7079
40	0,8507	1,0500	1,3031	1,6839	1,7963	1,9357	2,0211	2,1229	2,2503	2,4233	2,7045
41	0,8505	1,0497	1,3025	1,6829	1,7952	1,9343	2,0195	2,1212	2,2482	2,4208	2,7012
42	0,8503	1,0494	1,3020	1,6820	1,7941	1,9330	2,0181	2,1195	2,2463	2,4185	2,6981
43	0,8501	1,0491	1,3016	1,6811	1,7931	1,9317	2,0167	2,1179	2,2445	2,4163	2,6951
44	0,8499	1,0488	1,3011	1,6802	1,7921	1,9305	2,0154	2,1164	2,2427	2,4141	2,6923
45	0,8497	1,0485	1,3006	1,6794	1,7911	1,9294	2,0141	2,1150	2,2411	2,4121	2,6896
46	0,8495	1,0483	1,3002	1,6787	1,7902	1,9283	2,0129	2,1136	2,2395	2,4102	2,6870
47	0,8493	1,0480	1,2998	1,6779	1,7894	1,9273	2,0117	2,1123	2,2380	2,4083	2,6846
48	0,8492	1,0478	1,2994	1,6772	1,7885	1,9263	2,0106	2,1111	2,2365	2,4066	2,6822
49	0,8490	1,0475	1,2991	1,6766	1,7878	1,9253	2,0096	2,1099	2,2351	2,4049	2,6800
50	0,8489	1,0473	1,2987	1,6759	1,7870	1,9244	2,0086	2,1087	2,2338	2,4033	2,6778
51	0,8487	1,0471	1,2984	1,6753	1,7863	1,9236	2,0076	2,1076	2,2325	2,4017	2,6757
52	0,8486	1,0469	1,2980	1,6747	1,7856	1,9227	2,0066	2,1066	2,2313	2,4002	2,6737
53	0,8485	1,0467	1,2977	1,6741	1,7849	1,9219	2,0057	2,1055	2,2301	2,3988	2,6718
54	0,8483	1,0465	1,2974	1,6736	1,7843	1,9211	2,0049	2,1046	2,2289	2,3974	2,6700
55	0,8482	1,0463	1,2971	1,6730	1,7836	1,9204	2,0040	2,1036	2,2278	2,3961	2,6682
56	0,8481	1,0461	1,2969	1,6725	1,7830	1,9197	2,0032	2,1027	2,2268	2,3948	2,6665
57	0,8480	1,0459	1,2966	1,6720	1,7825	1,9190	2,0025	2,1018	2,2258	2,3936	2,6649
58	0,8479	1,0458	1,2963	1,6716	1,7819	1,9183	2,0017	2,1010	2,2248	2,3924	2,6633
59	0,8478	1,0456	1,2961	1,6711	1,7814	1,9177	2,0010	2,1002	2,2238	2,3912	2,6618
60	0,8477	1,0455	1,2958	1,6706	1,7808	1,9170	2,0003	2,0994	2,2229	2,3901	2,6603
61	0,8476	1,0453	1,2956	1,6702	1,7803	1,9164	1,9996	2,0986	2,2220	2,3890	2,6589
62	0,8475	1,0452	1,2954	1,6698	1,7799	1,9158	1,9990	2,0979	2,2212	2,3880	2,6575
63	0,8474	1,0450	1,2951	1,6694	1,7794	1,9153	1,9983	2,0971	2,2204	2,3870	2,6561
64	0,8473	1,0449	1,2949	1,6690	1,7789	1,9147	1,9977	2,0965	2,2195	2,3860	2,6549
65	0,8472	1,0448	1,2947	1,6686	1,7785	1,9142	1,9971	2,0958	2,2188	2,3851	2,6536
66	0,8471	1,0446	1,2945	1,6683	1,7781	1,9137	1,9966	2,0951	2,2180	2,3842	2,6524
67	0,8470	1,0445	1,2943	1,6679	1,7776	1,9132	1,9960	2,0945	2,2173	2,3833	2,6512
68	0,8469	1,0444	1,2941	1,6676	1,7772	1,9127	1,9955	2,0939	2,2166	2,3824	2,6501
69	0,8469	1,0443	1,2939	1,6672	1,7769	1,9122	1,9949	2,0933	2,2159	2,3816	2,6490
70	0,8468	1,0442	1,2938	1,6669	1,7765	1,9118	1,9944	2,0927	2,2152	2,3808	2,6479

Appendix E

Table E1: Table of χ^2

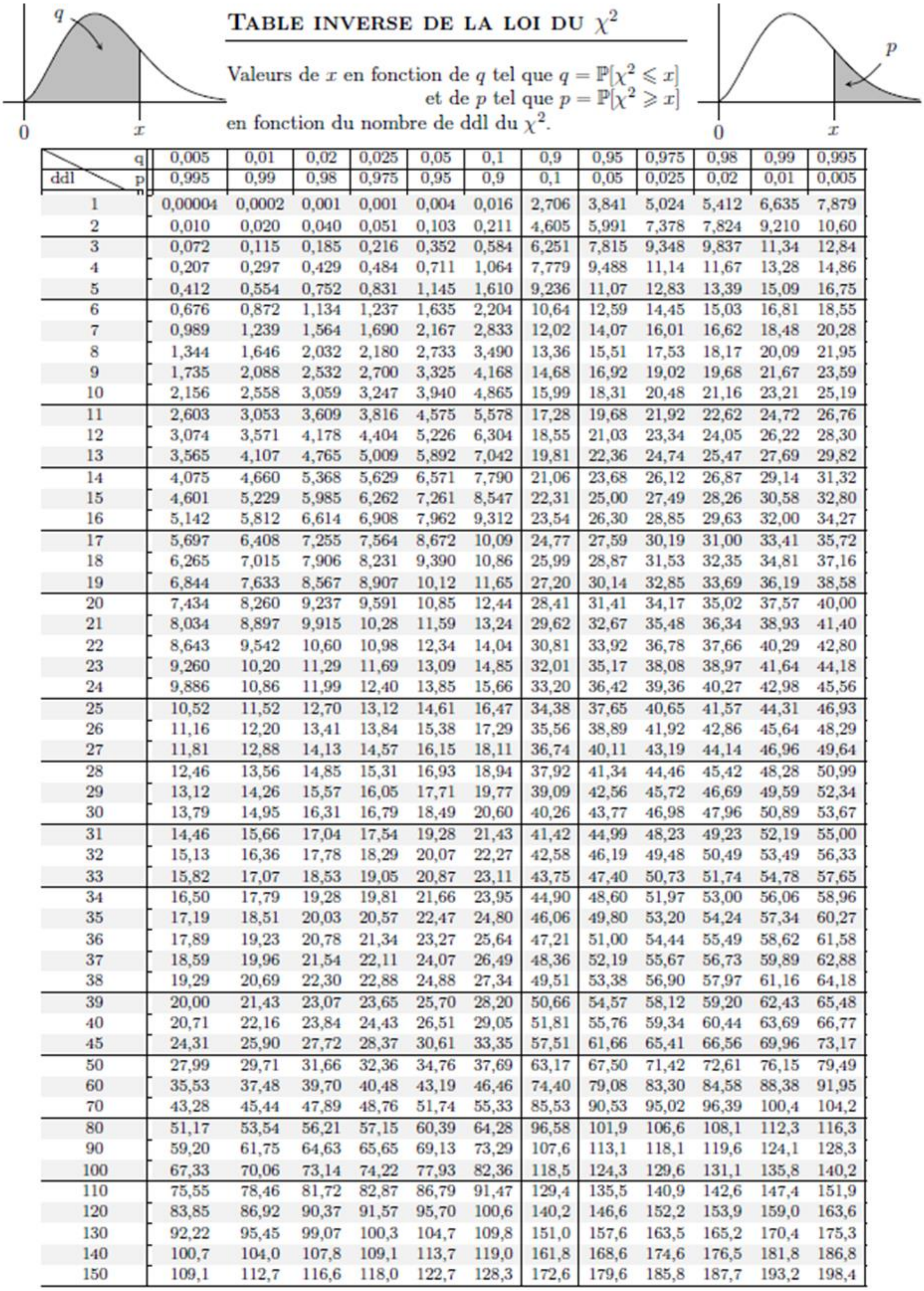


TABLE INVERSE DE LA LOI DU χ^2

Valeurs de x en fonction de q tel que $q = \mathbb{P}[\chi^2 \leqslant x]$
et de p tel que $p = \mathbb{P}[\chi^2 \geqslant x]$
en fonction du nombre de ddl du χ^2.

q	0,005	0,01	0,02	0,025	0,05	0,1	0,9	0,95	0,975	0,98	0,99	0,995
ddl p n	0,995	0,99	0,98	0,975	0,95	0,9	0,1	0,05	0,025	0,02	0,01	0,005
1	0,00004	0,0002	0,001	0,001	0,004	0,016	2,706	3,841	5,024	5,412	6,635	7,879
2	0,010	0,020	0,040	0,051	0,103	0,211	4,605	5,991	7,378	7,824	9,210	10,60
3	0,072	0,115	0,185	0,216	0,352	0,584	6,251	7,815	9,348	9,837	11,34	12,84
4	0,207	0,297	0,429	0,484	0,711	1,064	7,779	9,488	11,14	11,67	13,28	14,86
5	0,412	0,554	0,752	0,831	1,145	1,610	9,236	11,07	12,83	13,39	15,09	16,75
6	0,676	0,872	1,134	1,237	1,635	2,204	10,64	12,59	14,45	15,03	16,81	18,55
7	0,989	1,239	1,564	1,690	2,167	2,833	12,02	14,07	16,01	16,62	18,48	20,28
8	1,344	1,646	2,032	2,180	2,733	3,490	13,36	15,51	17,53	18,17	20,09	21,95
9	1,735	2,088	2,532	2,700	3,325	4,168	14,68	16,92	19,02	19,68	21,67	23,59
10	2,156	2,558	3,059	3,247	3,940	4,865	15,99	18,31	20,48	21,16	23,21	25,19
11	2,603	3,053	3,609	3,816	4,575	5,578	17,28	19,68	21,92	22,62	24,72	26,76
12	3,074	3,571	4,178	4,404	5,226	6,304	18,55	21,03	23,34	24,05	26,22	28,30
13	3,565	4,107	4,765	5,009	5,892	7,042	19,81	22,36	24,74	25,47	27,69	29,82
14	4,075	4,660	5,368	5,629	6,571	7,790	21,06	23,68	26,12	26,87	29,14	31,32
15	4,601	5,229	5,985	6,262	7,261	8,547	22,31	25,00	27,49	28,26	30,58	32,80
16	5,142	5,812	6,614	6,908	7,962	9,312	23,54	26,30	28,85	29,63	32,00	34,27
17	5,697	6,408	7,255	7,564	8,672	10,09	24,77	27,59	30,19	31,00	33,41	35,72
18	6,265	7,015	7,906	8,231	9,390	10,86	25,99	28,87	31,53	32,35	34,81	37,16
19	6,844	7,633	8,567	8,907	10,12	11,65	27,20	30,14	32,85	33,69	36,19	38,58
20	7,434	8,260	9,237	9,591	10,85	12,44	28,41	31,41	34,17	35,02	37,57	40,00
21	8,034	8,897	9,915	10,28	11,59	13,24	29,62	32,67	35,48	36,34	38,93	41,40
22	8,643	9,542	10,60	10,98	12,34	14,04	30,81	33,92	36,78	37,66	40,29	42,80
23	9,260	10,20	11,29	11,69	13,09	14,85	32,01	35,17	38,08	38,97	41,64	44,18
24	9,886	10,86	11,99	12,40	13,85	15,66	33,20	36,42	39,36	40,27	42,98	45,56
25	10,52	11,52	12,70	13,12	14,61	16,47	34,38	37,65	40,65	41,57	44,31	46,93
26	11,16	12,20	13,41	13,84	15,38	17,29	35,56	38,89	41,92	42,86	45,64	48,29
27	11,81	12,88	14,13	14,57	16,15	18,11	36,74	40,11	43,19	44,14	46,96	49,64
28	12,46	13,56	14,85	15,31	16,93	18,94	37,92	41,34	44,46	45,42	48,28	50,99
29	13,12	14,26	15,57	16,05	17,71	19,77	39,09	42,56	45,72	46,69	49,59	52,34
30	13,79	14,95	16,31	16,79	18,49	20,60	40,26	43,77	46,98	47,96	50,89	53,67
31	14,46	15,66	17,04	17,54	19,28	21,43	41,42	44,99	48,23	49,23	52,19	55,00
32	15,13	16,36	17,78	18,29	20,07	22,27	42,58	46,19	49,48	50,49	53,49	56,33
33	15,82	17,07	18,53	19,05	20,87	23,11	43,75	47,40	50,73	51,74	54,78	57,65
34	16,50	17,79	19,28	19,81	21,66	23,95	44,90	48,60	51,97	53,00	56,06	58,96
35	17,19	18,51	20,03	20,57	22,47	24,80	46,06	49,80	53,20	54,24	57,34	60,27
36	17,89	19,23	20,78	21,34	23,27	25,64	47,21	51,00	54,44	55,49	58,62	61,58
37	18,59	19,96	21,54	22,11	24,07	26,49	48,36	52,19	55,67	56,73	59,89	62,88
38	19,29	20,69	22,30	22,88	24,88	27,34	49,51	53,38	56,90	57,97	61,16	64,18
39	20,00	21,43	23,07	23,65	25,70	28,20	50,66	54,57	58,12	59,20	62,43	65,48
40	20,71	22,16	23,84	24,43	26,51	29,05	51,81	55,76	59,34	60,44	63,69	66,77
45	24,31	25,90	27,72	28,37	30,61	33,35	57,51	61,66	65,41	66,56	69,96	73,17
50	27,99	29,71	31,66	32,36	34,76	37,69	63,17	67,50	71,42	72,61	76,15	79,49
60	35,53	37,48	39,70	40,48	43,19	46,46	74,40	79,08	83,30	84,58	88,38	91,95
70	43,28	45,44	47,89	48,76	51,74	55,33	85,53	90,53	95,02	96,39	100,4	104,2
80	51,17	53,54	56,21	57,15	60,39	64,28	96,58	101,9	106,6	108,1	112,3	116,3
90	59,20	61,75	64,63	65,65	69,13	73,29	107,6	113,1	118,1	119,6	124,1	128,3
100	67,33	70,06	73,14	74,22	77,93	82,36	118,5	124,3	129,6	131,1	135,8	140,2
110	75,55	78,46	81,72	82,87	86,79	91,47	129,4	135,5	140,9	142,6	147,4	151,9
120	83,85	86,92	90,37	91,57	95,70	100,6	140,2	146,6	152,2	153,9	159,0	163,6
130	92,22	95,45	99,07	100,3	104,7	109,8	151,0	157,6	163,5	165,2	170,4	175,3
140	100,7	104,0	107,8	109,1	113,7	119,0	161,8	168,6	174,6	176,5	181,8	186,8
150	109,1	112,7	116,6	118,0	122,7	128,3	172,6	179,6	185,8	187,7	193,2	198,4