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A theoretical study of air change in Italian schools: energetic aspects, air quality and Sars-CoV-2 infection risk assessment

Part 1

Approccio teorico sul ricambio d'aria nelle scuole italiane: aspetti energetici, qualità dell'aria e valutazione del rischio di infezione da Sars-CoV-2

Parte 1

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Abstract

Schools are definitely among the highest densely occupied indoor environments with continuous occupation. According to the present knowledge about airborne carried diseases, the infection risk for SARS-CoV-2 could reach to significant values especially in poor ventilating conditions. The infection risk can be reduced by dilution of the viral agent concentration, provided by air-change, whether by infiltration, aeration (window opening) or mechanical ventilation. The present work, after a brief survey on ventilation requirements for schools in Italy, compares different strategies to account for dilution both in terms of infection risk control and of energetic and comfort aspects.
The paper is split into two parts: this part 1 deals with energetic aspects, while the second one will examine air quality and Sars-CoV-2 risk assessment. Each part has its own specific nomenclature and methodology.

Keywords:

- SARS-CoV-2
- Mechanical ventilation
- Air change
- Infection risk
- Airborne disease

Sommario

Le scuole sono sicuramente gli ambienti a più elevato tasso di occupazione continuo. Secondo le attuali conoscenze a proposito delle infezioni che si possono diffondere per via aerobica, il rischio di contagio per SARS-CoV-2 può raggiungere valori elevati soprattutto negli ambienti con scarsa ventilazione. La riduzione del rischio si può ottenere anche attraverso la diluizione della concentrazione dell'agente virale, che avviene per infiltrazione d'aria, aerazione (apertura delle superfici mobili, finestre), ventilazione meccanica. Il lavoro, dopo una sintetica disamina dei requisiti italiani di qualità dell'aria nelle scuole, confronta le diverse strategie per la diluizione sia in termini di contenimento del rischio di contagio sia in termini energetici e di comfort.
L'articolo si divide in due parti: la parte 1 tratterà gli aspetti energetici, la seconda i temi della qualità dell'aria e del rischio di infezione da Sars-CoV-2. Ciascuna parte ha la propria terminologia e metodologia.

Parole chiave:

- SARS-CoV-2
- Ventilazione meccanica
- Ricambio d'aria
- Rischio di infezione
- Malattie trasmesse per via aerea

NOMENCLATURE

t: time [h, s]
V: volume [m³]
rn: fresh (outdoor) air renewal factor [h⁻¹]
ρ: air density [kg m⁻³]
ρ_{ref}: air density at reference conditions [kg m⁻³]
T: temperature [°C]
T_e: outdoor temperature [°C]
T_i: initial temperature [°C]
T_f: final temperature [°C]
u: average windspeed [m s⁻¹]
a: thermal diffusivity [m² s⁻¹]
Bi: Biot number
Fo: Fourier number

Introduction

Schools are among the highest densely occupied environments with continuous occupation. It can be understood that during the Sars-CoV-2 pandemic special attention was given in order to perform an accurate evaluation of the infection risk in the classroom indoor environment, with the different double goal of fighting the pandemic and maintaining the fundamental services for the community (i.e. schools) as active as possible. The school re-opening programme after lockdown periods has drawn immediate attention to health and safety condition, then to ventilation, since it is ever more widely supported that the SARS-CoV-2 virus can survive as airborne [1]. A consistent review study [2] analyzes how different factors such as ventilation rates, direction of airflows, and relative position of susceptible and infected individuals can affect the probability of infection in the indoor environment with several airborne diseases.

The Wells-Riley model [3] has been recognized as a suitable predictive method for assessment of the infection risk for air carried particles, as widely supported by recent literature [4]. Several papers were published on the probability of infection in indoor environments according to different HVAC plant type [5], and special attention was also given to the context of school rooms. Virologist Christian Drosten recently stressed on the importance of ventilation for German schools [6], stating that ventilation is a major prerequisite to run schools in a healthy mode.

The previously quoted papers evenly agree that a great deal in the reduction of infection risk is played by the dilution of viral charges by means of air change, that occurs through:

- infiltration from openings (windows), due to pressure difference between inside and outside;
- aeration from open windows, due to temperature/pressure difference between inside and outside;
- mechanical ventilation.

Air change implies as well effects on comfort and energy consumption, since infiltration and aeration do not control the internal air distribution and increase the net energy demand of the building with no chance of heat recovery. Indeed aeration by opening windows at regular intervals (i.e. at the class change) can cause sudden air temperature drops (in winter) then generating discomfort, while mechanical ventilation systems can be equipped with heat recuperators and provide a better air distribution and ventilation efficiency.

Materials and methods

Assessment of Italian rules

In Italy a National Decree from 1975 [7] (withdrawn in 1996 but still referred to) had set the technical rules for school buildings with special reference (for the scope of this work) to:

- floor area per occupant;
- window area per floor area, for daylighting;
- basic comfort conditions (temperature and relative humidity range) to be controlled by ventilation.

Unfortunately the Italian school building stock is quite poor in terms of ventilation systems; though in some Regions and in new buildings the systems may be present, those systems are sometimes of the type with air recirculation, that have their own well known critical aspects [5].

According to different school grades, the floor area per occupant ranges between 1.8 and 2.0 m², while the window area per floor area should range between 1/7 to 1/5.

Aeration, infiltration and ventilation models adopted

The main task of the paper is that of comparing, from the energetic and infection risk assessment points of view, the consequences of infiltration, aeration or ventilation in a school room.

The starting point is that of assuming an average school room based on the prescriptions of the Italian Decree [7] for a 25 people class. According to the decree the minimum floor area is 49 m², and 10 m² of window area are enough to satisfy the highest demanding 1/5 range window area / floor area requirement. Considering a ceiling height of 3 m the volume of the room is 147 m³.

A simplified model was built to account for window opening (aeration) and infiltration. The air in the room follows a "well-mix" model that also accounts for heat transfer between walls and ambient air, and for the contribution of the heating system. The initial air temperature and wall temperature is 20 °C.

The heat transfer between air and the walls is governed by a fixed convection coefficient that is 10 [W m⁻² K⁻¹], and the internal wall temperature follows the model of a semi-infinite wall, according to the following formula [8]:

$$\Theta = \mathrm{erf}(Y) + e^{Bi\cdot(1+Bi\cdot Fo)} \cdot erfc\left(Y + Bi\cdot\sqrt{Fo}\right)$$

Formula 1 – Semi-infinite wall temperature model response

Where

$$\mathrm{Y} = \frac{x}{2\sqrt{a\cdot t}}$$

Being *x* the considered depth, *t* the time [s], and

$$\Theta = \frac{T - T_i}{T_f - T_i}$$

Diffusivity is set to 8*10⁻⁷ m² s⁻¹.

The heat transfer surface area is taken as the total room inner surface except for the wall with windows, and is equal to 106.35 m².

The contribution of the heating system (radiator) is calculated from a peak power of 3.41 kW at winter design temperature, corresponding to a water supply temperature of 75 °C and reduces according to UNI EN 442 formulas, considering a minimum supply temperature of 55 °C at 16 °C of outdoor temperature, with a linear sliding supply temperature control. When the outdoor temperature increases above 16 °C, no further contribution by the heating system is considered.

To estimate the air flow from window opening [m³ s⁻¹] the model of UNI EN 16783-7:2018 [9] was referred to, with reference to the following formula (44):

$$Q = \frac{\rho_{ref}}{\rho} \cdot \frac{A_w}{2} \cdot \max\left(C_{wnd} \cdot u^2 ; C_{st} \cdot h_w \cdot \left|T - T_e\right|^{0,5}\right)$$

Formula 2 – Air flow from window opening

Where C_{st} is the coefficient taking into account stack effect in airing calculations equal to 0.0035 s⁻¹ K⁻¹, C_{wnd} is the coefficient taking into account wind speed in airing calculations equal to 0.001 s m⁻¹

and h_w the height of the center of window considered equal to 1,5 m.

The procedure to estimate infiltration is also presented by CIBSE [10], while here the air flow by infiltration is rather calculated according to UNI EN 12207:2017 [11] for different air-tightness classes of windows. For the opening of 10 m² assumed in this work, class 1 of air tightness corresponds to 75 m³ h⁻¹ of air infiltration, while class 2 corresponds to 39.9 m³ h⁻¹.

The school room is considered to operate from 8 to 13 hour, 5 days a week, from September 15th to June 15th, thus including the full winter season. Hourly weather data were assumed from UNI-CTI official database [12]. The following different Italian locations were selected:

- Padova, average wind speed 2.1 m s⁻¹, 2 383 HDD (Heating DegreeDays)
- Torino, average wind speed 0.9 m s⁻¹, 2 617 HDD (Heating DegreeDays)
- Roma, average wind speed 1.3 m s⁻¹, 1 415 HDD (Heating DegreeDays)
- Napoli, average wind speed 3.2 m s⁻¹, 1 034 HDD (Heating DegreeDays)

Results

Air change by window opening and room temperature

Considering the regular working schedule of a school, it is assumed that the window opening is likely to occur at the end of each class hour. Some simulations were run considering 5 min (300 s) and 10 min (600 s) of window opening time.

At first it is considered to only open ½ of total window surface, so 5 m², $h_w = 1.5$ m, $T_i = 20$ °C.

Figures 1 and 2 show the total volume of air change after 300 and 600 s of window opening, with 5 m², $h_w = 1.5$ m, $T_i = 20$ °C, for different average wind speed values and outdoor temperatures. It can be seen that the different wind speed only affects the result at mild outdoor temperatures.

Figures 3 and 4 show the final room air temperature after 300 and 600 s of window opening with 5 m², $h_w = 1.5$ m, $T_i = 20$ °C, for different average wind speed values and outdoor temperatures. It can be seen that small differences can be appreciated due to wind speed at mild outdoor temperature, whereas the effect of heating shut-off above 16 °C outdoor temperature can be significant.

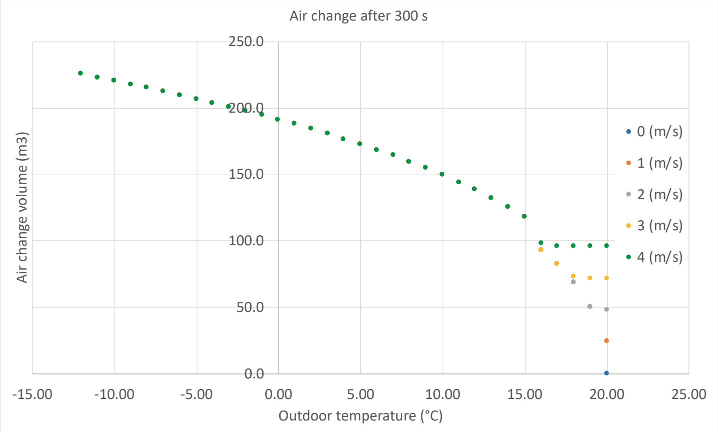

Figure 1 – Air change after 300 s, 5 m² of window opening

Figura 1 – Ricambio d'aria dopo 300 s, 5 m² di finestra aperta

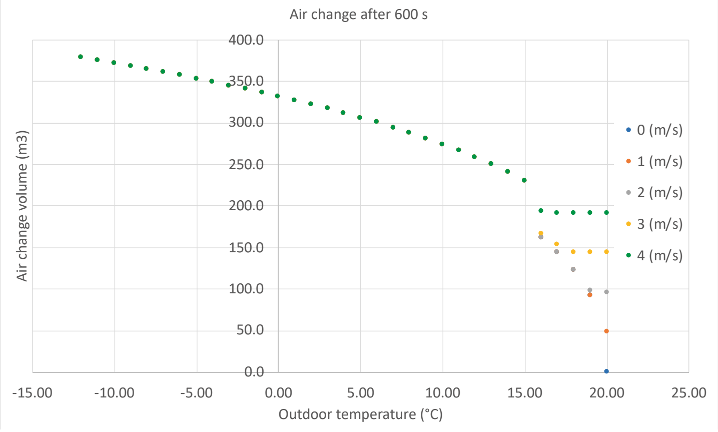

Figure 2 – Air change after 600 s, 5 m² of window opening

Figura 2 – Ricambio d'aria dopo 600 s, 5 m² di finestra aperta

As it can be seen by comparing Figure 5 to Figure 2, if the window surface opening is doubled (from 5 to 10 m²), with $h_w = 1.5$ m, $T_i = 20$ °C, the effect doesn't obviously reach that of doubling the opening time.

Some calculations where then run for a better understanding of the problem. Figure 6 shows the influence of center window height on the total air change at the end of the 300 s period, while Figure 7 reports the effect of the initial air temperature on the total air change at the end of the 300 s opening period.

Energy & HVAC calculations

Following the air change calculations, it is interesting to consider the effect in the net energy need of the room. Thermal need for window opening summarizes the thermal energy need to restore T_i both on the ambient air side and on the wall side.

The thermal energy needs for window opening and infiltration were compared to those generated by a mechanical ventilation system providing supply and extraction for 735 m³ h⁻¹ (*rn* of 5 as per the Law), with a recuperator efficiency referred to sensible heat of 75%, and an electric consumption of 180 W. The system is considered to be operated 1206 h y⁻¹ (according to the previously assumed scheduling). The results are summarized in the following Table 1, considering the opening of 10 m² of window for 5 min at the end of each class hour. As it can be seen, the winter loss due to window opening and infiltration,

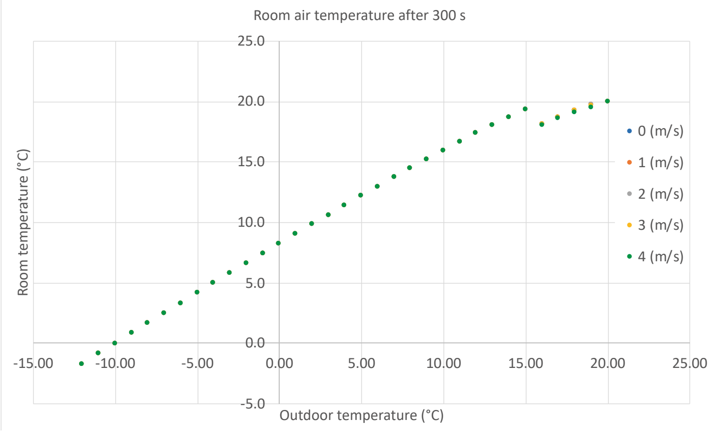

Figure 3 – Room air temperature after 300 s, 5 m² of window opening

Figura 3 – Temperatura dell'aria nel locale dopo 300 s, 5 m² di finestra aperta

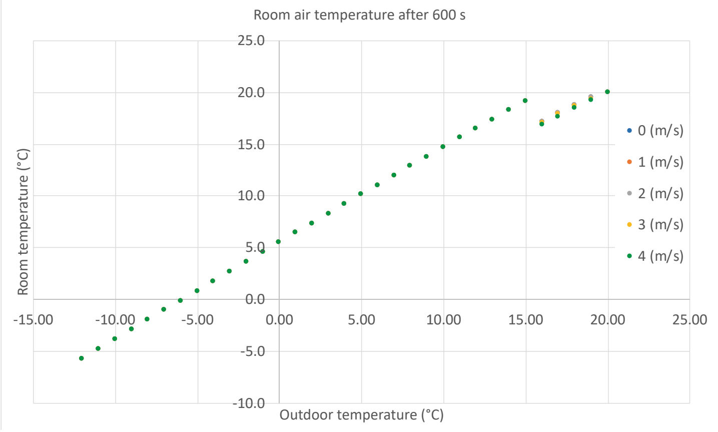

Figure 4 – Room air temperature after 600 s, 5 m² of window opening

Figura 4 – Temperatura dell'aria nel locale dopo 600 s, 5 m² di finestra aperta

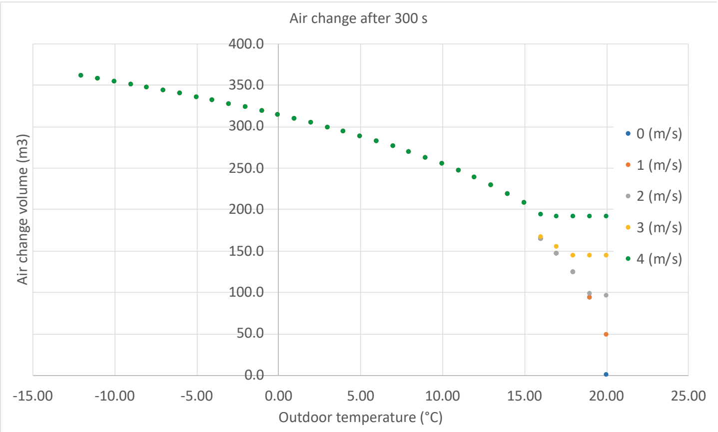

Figure 5 – Air change after 300 s, 10 m² of window opening

Figura 5 – Ricambio d'aria dopo 300 s, 10 m² di finestra aperta

Table 1 – Net energy balances (recuperator efficiency 0,75)

Tabella 1 – Fabbisogno netto di energia (efficienza del recuperatore 0,75)

	Winter opening (kJ)	Winter infiltration (kJ)	Summer opening (kJ)	Summer infiltration (kJ)	Winter AHU kJ)	Summer AHU (kJ)
Padova	1 523 551	507 077	- 75 906	- 24 678	2 115 877	- 107 473
Torino	1 589 063	531 088	- 69 053	- 23 109	2 216 067	- 94 774
Napoli	692 132	250 936	- 199 168	- 63 071	1 047 079	- 258 664
Roma	912 554	327 177	- 243 413	- 76 602	1 365 210	- 314 157

though never providing a *rn* above 2, can sum up to over 2 000 MJ. On the other hand the heat demand due to mechanical ventilation (AHU), though providing a *rn* of 5, reaches the value of 2 300 MJ. In terms of electric consumption, it amounts to 217.1 kWh y^{-1}.

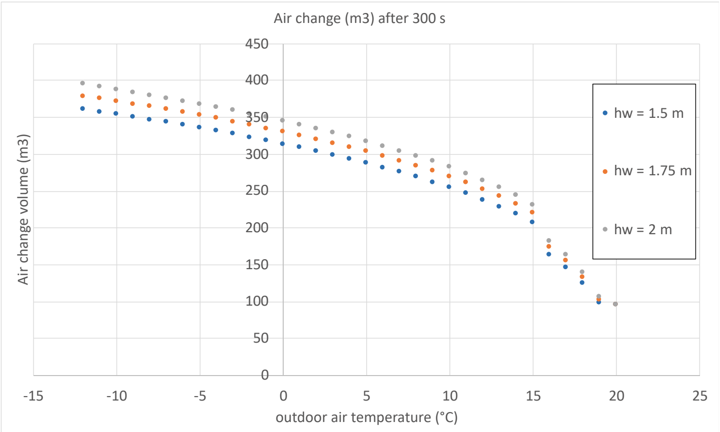

Figure 6 – Air change after 300 s, 10 m² of window opening

Figura 6 – Ricambio d'aria dopo 300 s, 10 m² di finestra aperta

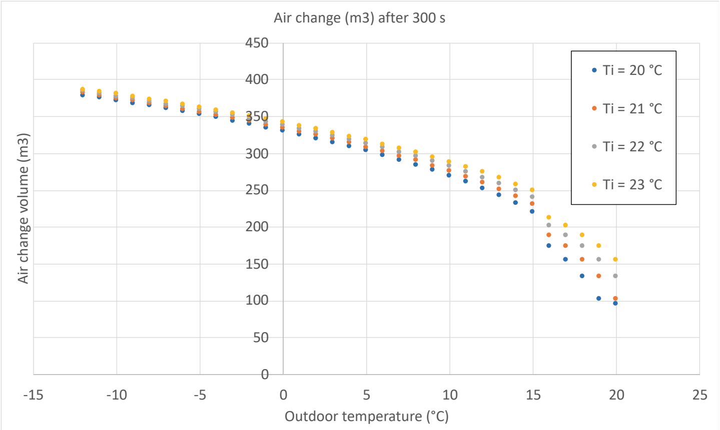

Figure 7 – Air change after 300 s, 10 m² of window opening

Figura 7 – Ricambio d'aria dopo 300 s, 10 m² di finestra aperta

Discussion and conclusions

The calculations and results shown are based on the assumption of a "well-mix" air model. This is a conservative approach both in terms of:

- air change ratio, since the flow rate established by the initial indoor-outdoor temperature difference is reduced during the opening by the consequent decrease of the average room air temperature;

and of

- energy calculations, since a reduction in air flow during the window opening time also reduces the temperature drop and then the energy need to restore initial conditions.

If these results are compared to the prescriptions of the Italian Law [7], it can be concluded that:

- a single hourly window opening, whether lasting 5 min or 10 min is never able to reach the recommended *rn* of 5 (735 m³ h^{-1} for the case considered);
- air change rate in mild conditions (around 10 °C outdoor air temperature) is quite poor, hardly reaching a *rn* of 1.5;
- room air temperature at the end of window opening time can be quite low especially at low temperatures, thus implying discomfort (partly compensated by radiant temperature), health risk and moreover for the task of this study, a high energy consumption.

CONFLICT OF INTEREST

The Authors declare the absence of economic or other types of conflicts of interest in all of the phases of the paper preparation.

REFERENCES

[1] Morawska L, Cao J., Airborne transmission of SARS-CoV-2: The world should face the reality. Environment International 2020; 139; 105730; https://doi.org/10.1016/j.envint.2020.105730

[2] Ai Z.T., Melikov A. K., Airborne spread of expiratory droplet nuclei between the occupants of indoor environments: a review. Indoor air 2018, https://doi.org/10.1111/ina.12465

[3] Sze To G.N., Chao C.Y.H., Review and comparison between the Wells–Riley and dose-response approaches to risk assessment of infectious respiratory diseases. Indoor air 2010; 20; 2-16; https://doi.org/10.1111/j.1600-0668.2009.00621.x

[4] Buonanno G., Stabile L., Morawska L., Estimation of airborne viral emission: Quanta emission rate of SARS-CoV-2 for infection risk assessment. Environment International 2020; 141; https://doi.org/10.1016/j.envint.2020.105794

[5] A. Cavallini, F. Busato, F. Pregliasco, Remarks on the air recirculation in HVAC sy- stems during the SARS-CoV-2 outbreak: the case of all-air ducted plants, AiCARR Journal, 2020, vol. 63 n.4, pp. 50-55, doi:10.36164/AiCARRJ.63.04.03

[6] Der Spiegel, 2021, https://www.spiegel.de/international/germany/interview-with-virologist-christian-drosten-i-am-quite-apprehensive-about-what-might-otherwise-happen-in-spring-and-summer-a-f22c0495-5257-426e-bddc-c6082d6434d5

[7] DM 18/12/1975, Norme tecniche aggiornate relative all'edilizia scolastica, ivi compresi gli indici di funzionalità didattica, edilizia ed urbanistica, da osservarsi nella esecuzione di opere di edilizia scolastica (English Translation Technical Specification for school buildings), Official Bulletin from Italian Republic.

[8] Bonacina et. Al, Trasmissione del calore, Cleup Padova (IT), 1975

[9] UNI EN 16798-7:2018, Energy performance of buildings - Ventilation for buildings - Part 7: Calculation methods for the determination of air flow rates in buildings including infiltration (Modules M5-5), UNI

[10] CIBSE Guide A: Environmental design, Ch 4.6 Assessing natural ventilation and air infiltration rates, 2006

[11] UNI EN 12207:2017, Windows and doors – permeability – classification, UNI

[12] https://www.cti2000.it/index.php?controller=news&action=show&newsid=34848, UNI-CTI Italian weather dataset

[13] Gammaitoni L, Nucci M. C., Using a Mathematical Model to Evaluate the Efficacy of TB Control Measures. Emerging Infectuous Diseases 1997, vol. 3, n. 3, 335-342