Impact of the new Chilean air-tightness regulation on indoor air pollution in dwellings with inefficient heating sources

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SUMMARY

In 2014, the Chilean Ministry of Housing and Urban Planning (MINVU) began to develop regulations for maximum levels of air infiltration in dwellings. This paper investigates the impacts of increased air-tightness on indoor air quality (IAQ) and energy use. The study uses computer simulations representative of social housing in Temuco, a city with heavy urban air pollution and cold winters. Results show infiltration measures produced reductions of -49% in air changes and -17% in heating loads. Emissions from six different types of wood, gas and paraffin burners including PM_{10}, $PM_{2.5}$, NO_2, CO, SO_2 and PAHs were modelled. changes of between -3% to +35% in individual contaminant concentrations, revealing that increased air-tightness does not necessarily imply a reduction in IAQ due to variations in deposition rates and reduced external pollutant ingress. As heater emissions exceeded pollutant concentration limits between 1-41% of the time, adopting cleaner heating technology is recommended.

PRACTICAL IMPLICATIONS

Based on actual circumstances in Chile, this modelling study demonstrates the consequences of increased air-tightness policies on (IAQ) and human health, in dwellings heated with low-efficiency stoves, a situation typical of low-income families in the south of the country. Furthermore, contaminant simulations can assist the calibration of the future infiltration regulations and suggest alternative heating provision in order to ensure positive health impacts for residents.

KEYWORDS: Infiltration; Indoor Air Quality; Social Housing; Heating; Chile.

1 INTRODUCTION

The regulation of energy efficiency standards for construction began in Chile in 2000 through the implementation of requirements for maximum allowable thermal transmittance in residential roofing elements, in the different climatic zones within the country. The "General Urbanism and Construction Ordinance" included these parameters in its article 4.1.10, aiming to reduce energy consumption at low cost (Ministerio de Vivienda y Urbanismo, 2014). In 2007, a stricter second stage of the regulation came into force, adding to its scope walls, windows and floors above ground level. Since 2014, MINVU has convened multidisciplinary teams, to carry out a third update of the energy legislation. This stage expanded its remit to include requirements for acoustics and indoor air quality (IAQ) in residential, educational and healthcare buildings. Provisional requirements for the future regulation were included in the documents "Ministerial Technical Standard 11 Draft" (NTM 11) (Bustamante, 2014). Its third chapter about Indoor Air Quality, stipulates the maximum permissible air infiltration rates through the construction envelope. Table 1 shows the infiltration proposal contained in NTM 11, which distinguishes two categories; i) Infiltration through cracks from the building envelope excluding doors and windows: measured in air changes per hour at 50 Pa (n50); and ii) Infiltration through cracks from doors and windows: measured in $m^3/hr/m^2$ at 100 Pa (q100).

Table 1. Maximum infiltration rates for housing according to NTM 11.

Thermal zones of Chile from A to I	A	B	C	D	E	**F**	G	H	I
Envelope without doors and windows (ach@50Pa)	-	6	9	8	8	**7**	4	6	4
Doors and windows ($m^3/hr/m^2$@100Pa)	-	30	30	10	10	**10**	7	7	7

From the ministerial working sessions, concerns arose about the possible increase of indoor air contamination as a consequence of increased air-tightness, especially in low-income dwellings in the southern regions of the country, where inefficient stoves are abundant and heating requirements are high. This study seeks to quantify the possible changes in the concentration of indoor pollutants, by comparing a baseline case corresponding to a typical Chilean example of social housing in terms of construction and infiltration rates, against a proposed case corresponding to the same house with the infiltration rates required by the NTM 11 standard. It also investigates possible health impacts arising from these scenarios.

2 MATERIALS AND METHODS

Case study area

The location chosen for this analysis was the city of Temuco (zone F in Table 1), located 670 kilometres south of Santiago. With an estimated population of 340,000, it has short summers and extended periods of cold, frosts and heavy rains. Substantial consumption of wood for heating and cooking, and standard social archetypes are typical of the location, making it ideal for a case study. It presents 2,500 heating degree days (base 18 °C) and no cooling is required. During the coldest month (July), temperature reaches -2.4°C with an average of +7.1°C (Sanhueza et al, 2012). Almost 70% of the population burns more than 39,400 m^3 of wood annually (Cereceda-Balic et al, 2012), using mostly moist timber due to its reduced cost (Lobos, 2001). Consequently, Temuco was declared'saturated by coarse and fine particulate matter' (Seremi Medio Ambiente Región Araucanía, 2012). Since 2008, the Chilean government has provided subsidies for thermal refurbishment and a replacement program for inefficient and polluting heaters (Cárdenas et al, 2014). The influence of external contaminants in Temuco was included in the computer modelling. The Chilean National Air Quality Information System (SINCA) database was consulted to obtain external measurements of the main pollutants considered in this study. Since PAH measurements were not available, average values were taken from Cereceda-Balic et al. (2012).

Table 2. External average concentrations of selected pollutants in the city of Temuco.

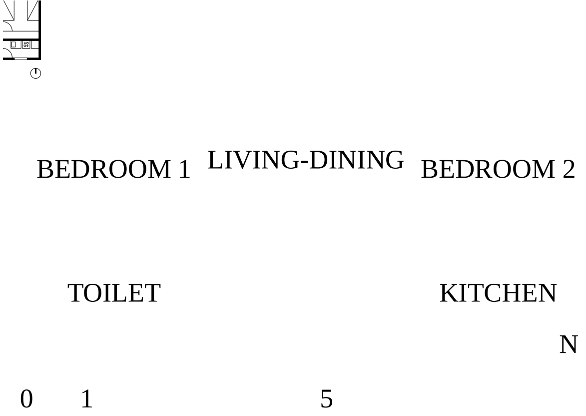
Pollutant *Limit ($\mu g/m^3$)	PM_{10} 120	$PM_{2.5}$ 50	NO_x 400	CO 30000	SO_2 250	PAH 100
Average value ($\mu g/m^3$)	67	53	57	1397	7.45	0.75
Percentage of the limit	56%	106%	14%	5%	3%	1%

*Maximum safe limit of contaminant concentration considered for this study (Ministerio Secretaría General de la Presidencia, 2015).

Case study design

The dwelling archetype was taken from the Design Guide for Energy Efficiency in Social Housing (Bustamante et al., 2009). It represents a typical house with a family room in the middle (Figure 1). Chilean families perform most daily activities together in the central room. Heating devices are usually placed there, leaving all internal doors open to improve heat distribution. During the night, when the stove is turned off, doors are closed trapping remaining pollutants in the sleeping areas.

Figure 1. Floor plan of the house selected for as a case study



Within the model, the configuration of occupancy and internal gains was constructed to reflect the weekly routine of a typical Chilean family composed of an adult couple and two children. The house was never completely unoccupied. The operation of heaters was set to achieve a typical temperature of 20°C in the living room from 7 am to midnight.

Collection of permeability data

To calculate the air transfer in the baseline case, the “Manual of Air-tightness of Buildings” (CITEC UBB & DECON UC, 2014) was used as a reference document. It contains infiltration measurements taken from Chilean houses, and doors and windows tested in laboratory environments. For construction, the database of the Annual Building Statistics Report (Instituto Nacional de Estadísticas, 2013) indicates that the most common material for housing in Temuco was wood for structure and cladding. The baseline case was therefore configured as follows:

a) The permeability of the thermal envelope excluding doors and windows: Information for this section was taken from Chapter 2 of the reference document (Figueroa & González, 2014). Infiltration was set to ’Wood’ at 24.6 ach/hr at 50 Pa.
b) The permeability of the most common windows and doors: (sliding windows with aluminium frames and plywood doors) was based on the reference document, infiltration of 18 $m^3/h/m^2$ at 100 Pa for windows and 29 $m^3/h/m^2$ at 100 Pa for doors.

Inefficient heating sources

To simulate contaminant emissions, the document Evaluation of Atmospheric Impact of Domestic Heating Systems (CENMA, 2011) was used as a reference. It contains measurements of the six most popular heating devices currently available in the Chilean market and considered representative of those used in Temuco (Table 3).

Table 3. List of devices measured by CENMA and their corresponding heating capacities.

Id	Technology	Brand and model	Max output (kW)
1	Gas radiant	Fensa FEL 1430	4.00
2	Gas forced convection	Rinnai Dynamo 15	3.80
3	Paraffin simple wick	Mademsa Foguita	2.55
4	Paraffin technological wick	Toyotomi Omni 230	6.74
5	Paraffin laser	Toyotomi LC-43	4.19
6	Wood double chamber	Amesti Double Chamber	7.00

For each device, the emissions rates of the selected pollutants were measured via wind tunnel testing (mass/time). These values are presented in Table 4. Cells with N/A represent cases where no emission was detected. Since the emission rates presented by CENMA were obtained using the heaters at their maximum capacities (kW), the time and intensity of use of each device to maintain an internal temperature of 20 °C inside the case study will also vary. The emission rates of each heater decrease in direct proportion to the reduction of their power output. Consequently, these were adjusted according to the heating demand of the baseline and proposed future cases. Table 4 presents the rates adjusted to the heating demand of the baseline case, calculated in 2.93 kW using the 99.6% ASHRAE design conditions (ASHRAE,2013). For the proposed case, the calculated heating demand was 2.61 kW due to less infiltration. Therefore, the adjusted emission rates were 12% lower than the baseline case to compensate.

Table 4. Emission rates for each heater. ORI: CENMA's original measurements.

Id	PM$_{10}$ (mg/min)		PM$_{2.5}$ (mg/min)		NO$_2$ (mg/min)		CO (mg/min)		SO$_2$ (mg/min)		PAH (µg/min)	
	ORI	**ADJ**	ORI	**ADJ**	ORI	**ADJ**	ORI	**ADJ**	ORI	**ADJ**	ORI	**ADJ**
1	N/A	**N/A**	N/A	**N/A**	1.20	**0.88**	24.44	**17.90**	N/A	**N/A**	N/A	**N/A**
2	N/A	**N/A**	N/A	**N/A**	0.65	**0.50**	8.02	**6.18**	N/A	**N/A**	N/A	**N/A**
3	0.37	**0.43**	0.29	**0.33**	1.92	**2.21**	26.20	**30.10**	1.24	**1.42**	20	**23**
4	0.19	**0.08**	0.14	**0.06**	1.61	**0.70**	5.32	**2.31**	2.52	**1.10**	23	**10**
5	0.15	**0.10**	0.15	**0.10**	1.80	**1.26**	8.00	**5.59**	2.29	**1.60**	N/A	**N/A**
6	0.05	**0.02**	0.05	**0.02**	0.11	**0.05**	2.55	**1.07**	N/A	**N/A**	248	**104**

ADJ: Rates adjusted to an energy output of 2.93 kW corresponding to the baseline case.
1. Gas radiant – 2. Gas forced convection – 3. Paraffin simple wick – 4. Paraffin technological wick – 5. Paraffin laser – 6. Wood double chamber

The measurements made by CENMA used dichotomous samplers to measure PM$_{10}$ and PM$_{2.5}$ separately. This allowed the simulation of both fractions independently according to their specific deposition rates and physical properties.

Selected contaminants

To perform the computational simulation of contaminants, a database of physical properties and deposition rates for the pollutants was created from empirical sources. Physical properties of PAH were taken from the Database of Air Liquide (2015) and Chandra, et al. (1994). Deposition rates were measured differently for particles and gases: particles were set to hourly deposition rates (1/h) and gases to deposition velocities (cm/s) based on the studies of He et al. (2005), Chang, et al. (2003) and Sehmel (1980).

Table 5. Physical properties and mean hourly limit ($\mu g/m^3$) for each contaminant.

	State of matter	Molecular weight (g/mol)	Specific heat (J/kg*K)	Mean diameter (μm)	Effective density (kg/m^3)	Particle deposition rate (1/h)	Gas deposition vel (cm/s)	[b] **Limit ($\mu g/m^3$)**
PM_{10}	Solid	-	-	10	2000	6.1	-	**120**
$PM_{2.5}$	Solid	-	-	2.5	2000	2.9	-	**50**
NO_2	Gas	46	806	-	3.40	-	1.9	**400**
CO	Gas	28	1040	-	1.18	-	0.1	**30000**
SO_2	Gas	64	640	-	2.76	-	3.8	**250**
PAH [a]	Gas	252	1012	-	2.40	-	1	**100**

[a] *Concentration of PAH emissions measured in gas-phase.* [b] Maximum pollutant concentration limits

To assess potential health impacts from exposure to polluted air, concentration limits for each pollutant were taken from the Chilean Primary Air Quality Standards (Ministerio Secretaría General de la Presidencia, 2015), which gives maximum hourly concentrations in $\mu g/m^3$. For PAHs, this limit was taken from the National Institute for Occupational Safety and Health recommendation (NIOSH REL, 2013).

CONTAM and IESVE simulations

Two different validated software packages were used to obtain results for this study. The first CONTAM, developed by the US National Institute of Standards and Technology (NIST) is able to perform dynamic simulations of pollutants and their transportation (Emmerich, 2001). However, it cannot independently calculate hygrothermal conditions, which are necessary to simulate the effects of dynamic temperature on airborne pollutants. To overcome this, a second software package, IESVE (Integrated Environmental Solutions, 2015), was used to supply the missing data. Equivalent archetypes and conditions of infiltration were created in both models. Simulations were performed from April 1 to September 30 (the cold season) in 4392 hourly time-steps. The infiltration rates calculated in CONTAM were exported to IESVE for internal temperature calculations. Subsequently, resultant temperatures were sent back to CONTAM for the final simulations.

3 RESULTS

The results of average changes in pollutant concentrations are presented in Table 6. Values are presented in percentages with respect to the established safe limits measured in $\mu g/m^3$.

Table 6. Percentage of mean contaminant concentration regarding the limit of each pollutant.

Contam	PM_{10}		$PM_{2.5}$		NO_2		CO		SO_2		PAH	
Limit	120		50		400		30000		250		100	
Id	Base	Prop	Base	Prop	Base	Prop	Base	Prop	Base	Prop	Base	Prop
1					52%	54%	51%	67%				
2					31%	32%	20%	25%				
3	33%	31%	**109%**	**108%**	**126%**	**134%**	83%	**111%**	77%	78%	8%	9%
4	10%	8%	32%	26%	42%	44%	9%	11%	60%	60%	4%	4%
5	11%	9%	43%	39%	73%	77%	18%	23%	86%	88%		
6	5%	4%	20%	16%	6%	5%	6%	7%			35%	40%

1. Gas radiant – 2. Gas forced convection – 3. Paraffin simple wick – 4. Paraffin technological wick – 5. Paraffin laser – 6. Wood double chamber

The percentage of hours when contamination surpassed the recommended limits are presented in Table 7. Paraffin wick heaters (3) again showed extended periods of contamination excess with almost half of the time of the simulated period.

Table 7. Percentage of time from a total of 4392 hours when concentrations surpassed the limit.

Contam	PM_{10}		$PM_{2.5}$		NO_2		CO		SO_2		PAH	
Id	Base	Prop	Base	Prop	Base	Prop	Base	Prop	Base	Prop	Base	Prop
1					29%	34%	17%	26%				
2					3%		1%	1%				
3			41%	41%	40%	41%	31%	43%	39%	40%		
4					19%	24%			36%	39%		
5					36%	39%			40%	41%		
6											12%	17%

The variation of contamination from the existing to the retrofitted stock is presented in Table 8

The left columns contain results regarding heater type, where the accumulated risk was calculated by adding the concentration percentages of each pollutant with respect to its limit. The right side contains results regarding the average concentrations of each contaminant. The variation was calculated by subtracting the results of proposed and baseline cases.

4 DISCUSSION

The NTM 11 proposal proved to be effective in reducing infiltrations with 49% reduction in air change observed (mean flows 23.0 and 11.8 l/s). Heating loads were reduced by an average of -17% during the period of six months (2,851 kWh to 2,365 kWh). The results suggest that the calibration of the NTM 11 proposal was accurate in achieving the primary goals of increased air-tightness and energy efficiency gains. However, the limitations of this initial study are acknowledged: Calculations are representative of only one location and type of construction. Future work will look at a range of archetypes and construction material scenarios.

When comparing heaters, heater 3 (paraffin simple wick) was the only device which exceeded the recommended thresholds, posing a major risk to health. In general terms, paraffin systems were the most contaminant, because of their emissions of NO_2, CO and SO_2. Nevertheless, a significant reduction of CO concentrations was observed in heaters 4 and 5 due to the inclusion of a sealed chamber for gas recirculation, creating better combustion, although the emissions of SO_2 remained high even with this additional technology. Conversely, gas burners created less pollution compared to paraffin, averaging 56% and 27% in heaters 1 and 2 respectively. The inclusion of a hidden burner with assisting impulsion fans helped substantially in reducing emissions by more than 50%. The least polluting device was heater 6, a biomass burner. In this heater, the presence of an exhaust flue and a dual combustion chamber proved to be useful, but insufficient to control PAH emissions, which reached 40% of the limit in the proposed case. Because all heaters exceeded limits at some point, all heaters posed risk to occupants who inhabit rooms with no direct venting to the outside air.

Overall, greater air-tightness did not necessarily imply an increase of contaminants as expected and in some cases presented almost no or negative variations. This was due the existence of other variables with influence over contaminants such as physical properties of gases and external levels of pollution. It was observed that cases such as heaters 1 and 3, with predominant emissions of light gases such as CO and NO_2, concentrations increased to a greater extent. This is explained by the slow rate of deposition of gases. On the other hand, heavier contaminants with higher deposition rates such as PM_{10} and $PM_{2.5}$ showed negative variations. Due to the intermittent operation of heaters, their concentration decreased faster during power-off times. Another factor of influence was external urban pollution. Greater air-tightness meant less infiltration of contaminants, especially for PM_{10} and $PM_{2.5}$, with elevated external average concentrations of 56% and 106% respectively (Table 2). Behaviour change around window opening, would increase the impact of external sources whilst reducing internal emissions, however the cold temperatures and heating costs may prevent this.

5 CONCLUSIONS

This case study analysed an energy efficiency measure and indoor airborne pollutant concentrations emitted from six types of heaters and outdoor sources in Temuco. The limitations of this study are acknowledged, nonetheless despite uncertainties, the results provide important indications of policy impacts. It appears NTM 11 is effective in reducing air infiltration by 49% and of heating loads by 17%. Increased air-tightness resulted in both increases and reductions in IAQ when NTM infiltration levels were applied. Results suggest that all heaters present a health risk to varying extents and current policies to provide subsidies for thermal refurbishment and replacement of inefficient and polluting heaters should run concurrently. For paraffin heaters, the increase of total concentrations was up to 35%. For wood and gas heaters, the high emission of PM and PAH generated a negligible increase (or even a decrease in indoor concentrations). Contaminants with faster deposition rates were not influenced significantly.. Heaters with dual burning chamber technology provided better combustion of gases such as CO, NO_2 and SO_2, which in turn helped to reduce contaminant concentrations. Reductions in ingress of external sources was another influencing factor. Periods of excess of contamination were observed in all heaters, which indicates that an auxiliary ventilation system may be necessary to ensure the health of occupants. This study is proposed as the basis for further investigation of ventilation behaviour and ventilation systems for simulation in other regions of Chile.

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