**The effect of prevailing climate, outdoor pollution levels and ventilation rates on indoor air quality in social housing in Almaty, Kazakhstan**

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**Abstract:** Increased ventilation rates were one way of reducing Covid risks. However, there are some negative health effects associated with increased air flow rates if the external air is polluted. There have been very few studies of residential indoor air quality (IAQ) in Kazakhstan. For this research existing low-income, mid-rise and naturally ventilated social housing in the city of Almaty were modelled to simulate indoor contaminant levels for different ventilation rates and climatic conditions. CONTAM v3.4 was used to model indoor concentrations of gaseous nitrogen dioxide (NO2) and particulate matter (PM2.5) – chosen for their negative impacts on cardio-respiratory health. Outdoor levels of NO2 and PM2.5 were provided by an air quality monitoring station a few kilometres from the housing. NO2 and PM2.5 levels were estimated to investigate how combinations of weather and ventilation rate might influence IAQ. Combinations of particular wind speeds and directions, coupled to window opening patterns, could lead to indoor levels of NO2 and PM2.5 that were higher than are recommended in health standards. Further work will carry out field monitoring of indoor pollutants to calibrate the accuracy of the CONTAM model and provide data on existing IAQ levels in Kazakhstan’s social housing stock.

**Keywords:** indoor air quality, health, weather

**1. Introduction:**

Indoor and outdoor air quality are well established determinants of population health and wellbeing. The World Health Organisation has established air quality guidelines for several air pollutants known to be harmful to human health (WHO 2021), including particulate matter (PM2.5) and nitrogen dioxide (NO2). Based on population weighted, annual average PM2.5 concentration (μg/m³) data from 2018 to 2021, Kazakhstan currently ranks 23rd among the world's most polluted countries (IQAir 2021). There has been evidence that elevated PM2.5 and NO2 concentrations are associated with adverse health effects, like respiratory and cardiovascular diseases (Brook et al. 2010; Pope Iii et al. 2002; Yang et al. 2019; Zanobetti et al. 2009). Also, PM2.5 concentrations are associated with an increased risk of contracting the COVID-19 virus and the likelihood of experiencing more severe symptoms, including death, if infected (Cole, Ozgen & Strobl 2020; Wu et al. 2020).

Indoor residential exposure to PM2.5 and NO2 is becoming a public concern because most people spend majority of their time indoors. Indoor residential PM2.5 is mostly produced by smoking and cooking (Dimitroulopoulou et al. 2006; Hu & Zhao 2022), as well as by ambient PM2.5 entering the home through ventilation or envelope leakage. Indoor residential NO2 sources include gas stoves and outdoor concentrations. Total indoor concentrations of these pollutants are influenced by the relative distribution of outdoor and indoor sourced pollutants in the residence, which is dependent on housing characteristics. Indoor PM2.5 and NO2 concentrations are also influenced by socio-demographic characteristics, which could lead to different exposure patterns and health hazards in specific populations (Rotko et al. 2000; Shrubsole et al. 2016). Low-income households, for example, may be more susceptible to these impacts as they are more likely to live in smaller apartments within multifamily residences, thereby increasing the influence of indoor sources within their unit or from neighbouring flats. Also, low-income urban inhabitants are more likely to smoke and cook using gas stoves (Glasser et al. 2022), both of which can raise indoor PM2.5 and NO2 concentrations.

To date, a considerable number of existing social housing buildings in Kazakhstan are not equipped with mechanical ventilation systems, which results in natural ventilation being the only way to supply fresh air indoors. However, using natural ventilation for areas with high outdoor pollution levels could increase the risks of people being exposed to air pollutants. Over the last six years a stable high level of air pollution had been observed in Kazakhstan and ambient air pollution was a subject of numerous studies (Kerimray et al. 2020; Vinnikov, Tulekov & Raushanova 2020). However, little is known about the impact of ambient air pollution on indoor air quality in Kazakhstan.

The purpose of this study was to determine to what extent the ambient PM2.5 and NO2 concentrations and indoor emitted particles contribute to indoor PM2.5 and NO2 pollution in social housing apartment in Almaty, Kazakhstan, under differing meteorological conditions, particularly the prevailing wind direction for the analysed dates in summer and winter of 2021 as well as the steady state wind direction in relation to the orientation of the building. The results seek to contribute to a better understanding of how the outdoor air pollutants and occupants’ behaviours impact indoor air quality (IAQ) in Kazakhstan’s social housing.To achieve this objective, a naturally ventilated social housing apartment block in Almaty was simulated during the summer and winter seasons for different ventilation rates and prevailing climatic conditions. The outdoor PM2.5 and NO2 concentrations were obtained from an actual monitoring station. The indoor sources emission rates were estimated from a literature review. The multizone airflow and contaminant transport program CONTAM v3.4 was used to model indoor and ambient concentrations of NO2 and PM2.5.

**2. Methodology**

**2.1 Study area**

The study area was social housing apartments in Almaty (43.2220° N, 76.8512° E), which is a major city in southern Kazakhstan, with a population of 2 million people. Figure 1 shows the location of Almaty within Kazakhstan.



Figure 1. Location of Almaty within Kazakhstan

The average annual air temperature of Almaty is 9.4 0C. The average air temperature fluctuates in January from -18.4 to -1 0C and in July from 20.7 to 27.3 0C. Extreme summer temperatures can reach up to 41.7 0C, while winter temperatures can drop to -37.7 0C. Almaty has a ‘bowl-shaped’ topography and is located in the wind shadow of the Ile Alatau mountain range, where stagnant weather conditions are frequent, which lead to adverse environmental conditions. The situation is aggravated by the fact that the "wind rose" has been distorted in the metropolis. According to the National Hydrometeorological Service RSE ‘Kazhydromet’, over the past 30 years, the average wind speed has decreased from 6 to 1-2 metres per second (Koshegulova & Kon 2021). Calm weather and strong inversion layers suppressing vertical exchange are major reasons for the high levels of air pollution over the city (Zakarin et al. 2021).

Almaty is one of the leading cities in terms of the amount of social housing commissioned there. As part of the implementation of the “Nurly Zher” state programme, 3,065 apartments, with a total area of 239,700 m2, were put into operation in 2021, including, 1451 apartments to large families, working youth, and for socially vulnerable segments of the population (RK 2022). From 2012 the state program has been constructing affordable social housing corresponding to III and IV comfort classes in accordance with the requirements of state standards in the field of architecture, urban planning and construction (Mamin 2019). Economy class housing is distinguished by such parameters as the number of rooms, varying from 1 to 3 and about 15 m2 per person.

**2.2 Building**

A low-income residential complex, classified as class IV (economy class) according to the Kazakhstan building code, and located in Almaty’s North-west edge, was chosen for this study. This social housing building was commissioned in 2013 and includes a complex of 33 houses of different heights from four to nine storeys (Figure 2). Back in 2016-2017, cases of tilting houses were regularly detected due to the subsidence of the soil and violations of building standards. During cold periods, the building is supplied with district heating using solid fuel. The building is naturally ventilated, and outdoor air is supplied through window openings and infiltration. The complex is located within a two kilometre radius of a combined heat and power CHP-2 central heating plant and a waste processing plant.



Figure 2. View of the residential social housing complex studied in this research.

**2.3 Simulation parameters**

The average floor area per tenant in the simulation parameters for economy-class (IV) apartments was 15 square metres. The class IV apartments have one to two living rooms at most, as well as a shared bathroom. There are up to 9 square metres in the kitchen. Finished apartment quality is referred to as the simplest in terms of interior finishes that use inexpensive building materials and fixtures (KAZGOR 2007). Also, in comparison to the higher classes, the finishing work's internal surfaces are where the most deviations are permitted. Rods, plastered surfaces, as well as window and door slopes, have the largest vertical and horizontal deviations (mm per 1 m) with a simple and budget quality building finishing for class IV compared to improved or high-quality comfort classes (Nuguzhinov et al. 2004). CONTAM 3.4.03, which is an established and well-validated multi zone airflow and contaminant transport analysis program, was chosen as the primary tool for this study. A two-bedroom corner unit apartment with a total floor area of 54.84 m2. Figure 3 shows the CONTAM schematic plan layout of the apartment, with the modelled area in green. The apartment is located on the ground floor of a 4-storey high building, with a basement below it. The height of the basement and residential floors is 2.8 m from the finished floor to the bottom of the floor slab. There are three apartments on each floor, and the studied one is located at the northwest corner of the floor with windows facing north and south. Building dimensions were based on the architectural plans.

Each zone  contains an airflow path, represented as a ‘rhombus/diamond’  on the walls and floors, which is a CONTAM building component through which air can move between two adjacent zones. Each airflow path is provided with specific leakage value information that describes its flow characteristics. An even distribution of permeability was assumed across all surfaces. Leakage values were assigned to interior and exterior walls, wall joints, windows, doors, and ceilings based on ASHRAE’s effective leakage area (ASHRAE 2001) and previous modelling studies (Fabian et al. 2016; Underhill et al. 2018). CONTAM deposition rate sink model  was used to remove contaminants (PM2.5 and NO2) from zones. PM2.5 was modelled using a deposition rate of -0.19/h and -0.87/h for NO2 (Fabian, Adamkiewicz & Levy 2012; Long et al. 2001; Taylor et al. 2014).

Indoor air temperatures in summer and winter were set at 20 °C, according to the interstate standard GOST (GOST30494-2011 2013). Hourly values of weather conditions for a typical meteorological year (TMY) were obtained from the Meteonorm software in epw format. One week in August and one week in December were selected to represent hot and cold periods respectively. Hourly air pollution data from ‘ПНЗN3 (S) Ice Arena’ station located in the Alatau district of Almaty were obtained from KazHydroMet between 1st January 2021 and 31st December 2021.

CONTAM contaminant concentrations within the control area (living room) of an apartment were simulated using different combinations of airflow and contaminant state methods (Table1). Steady state and transient state airflow were simulated against transient contaminant concentrations, and this generated twenty scenario cases defined by season and window opening behaviour. Open windows are marked as ‘O’ and closed windows as ‘X’ in Table 1. The calculation time step in CONTAM allows the user to perform a combination of simulation method settings over a user-defined time period. For instance, to obtain a time history of contaminant concentrations under steady airflow conditions, "steady state airflow," which is a user-specified weather condition and in this study with a focus on changing the wind direction, was combined with "transient contaminant," which is a dynamic contaminant concentration from an external contaminant file simulation. Additionally, transient contaminant simulation and transient airflow simulation (Table 2) that use external weather data for the designated period are combined to produce time histories of contaminant concentrations (PM2.5 and NO2) under changing weather conditions. All simulation types used a 5-minute time step interval.

Table 1. *Variable case scenarios representing changes in season, window opening and airflow simulation patterns.*

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | Steady state airflow simulation | | | | | | | | | | | | | | | | | |
| Season | Winter | | | | | | | | Summer | | | | | | | | | |
| Wind direction | N/0° | | E/90° | | S/180° | | W/270° | | | N/0° | | E/90° | | S/180° | | W/270° | | |
| Window\* | X | O | X | O | X | O | X | O | | X | O | X | O | X | O | X | O |
| Case | *S1* | *S2* | *S3* | *S4* | *S5* | *S6* | *S7* | *S8* | | *S9* | *S10* | *S11* | *S12* | *S13* | *S14* | *S15* | *S16* |
|  | **Transient airflow simulation** | | | | | | | | | | | | | | | | | |
| Season | winter | | | | | | | | summer | | | | | | | | | |
| Window\* | X | | | | O | | | | | X | | | | O | | | | |
| Case | *TW1* | | | | *TW2* | | | | | *TS1* | | | | *TS2* | | | | |
| \*- windows during the cold season were open for two times a day for 30 minutes and during summer were open for the whole day from 8 a.m. to 8 p.m.; | | | | | | | | | | | | | | | | | | |

**3. Results**

Hourly average concentrations of total indoor PM2.5 and NO2 in the living room of the corner apartment were simulated for one week each during winter heating and summer cooling periods across several window opening and airflow scenarios. Overall, indoor concentrations are the sum of the effects of all sources within the unit and infiltration from outdoors. Indoor PM2.5 concentrations during the one-week winter period under transient contaminant simulation varied from 23.5 to 644.1 µg/m3, with an average of 166.2 µg/m3 for a closed window (TW1), and from 23.9 to 645.5 µg/m3, with an average of 167.7 µg/m3 for an open window (TW2) case (Figure 4). The mean outdoor modelled concentration of PM2.5 during the winter heating season (209 µg/m3) was significantly higher than the mean concentrations in the control area (166 µg/m3). Results of the Pearson correlation indicated that there is a significant large positive relationship between ambient PM2.5 concentration and indoor PM2.5, (*r*(167) = .944, *p* < .001), as shown in Table 2. Concentrations of mean indoor PM2.5 during the summer period varied from 4.4 to 48.0 µg/m3, with an average of 19.2 µg/m3 for both windows opening activity scenarios (Figure 5). Indoor PM2.5 reflect outdoor concentration levels.

Average concentrations of ambient NO2 from the state monitors were stable across all studied seasons, ranging from 0.9 to 1.2 µg/m3, with an average value of 1.0 µg/m3 (Table 2). There was an increase of indoor NO2 concentrations during cold periods, coinciding with cooking activities and minimum window opening behaviour (Figure 6), and an indoor decrease of NO2 during the summer period (Figure 7) with occasional peaks reaching 4.2 µg/m3. The NO2/TW1 and NO2/TW2 lines in Figure 6 overlap due to very small significant difference in NO2 pollutant concentration between window closed (*M* = 1.4, *SD* = 2.4) and window open condition (*M* = 1.4, *SD* = 2.4), *t*(168) = 2.5, *p* = .014, during cold season, according to the results of the paired t-test. Also, there is a non-significant NO2 concentration difference between window closed (*M* = 0.6, *SD* = 0.5) and window open state (*M* = 0.6, *SD* = 0.5), *t*(168) = 0.4, *p* = .683 for the summer period (Figure 7).

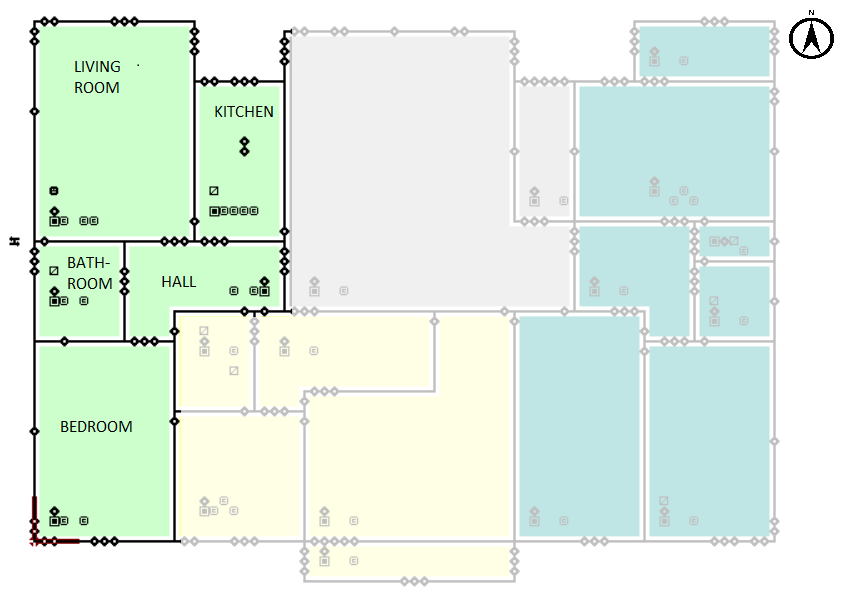


Figure 3. *CONTAM schematic floor layout, representing the Ground Floor apartments in a social housing building. Each apartment is divided into colour zones. Each zone contains airflow paths, pollutant sources and sinks which are represented as dots on walls and interior spaces.*

Table 2. Ambient *PM2.5 and NO2 concentrations for the specified period of 2021 and simulated values for indoor control area.*

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Transient airflows | Period | Values | Indoor PM2.5 µg/m3 | Outdoor PM2.5 µg/m3 | Indoor NO2 µg/m3 | Outdoor NO2 µg/m3 |
| window open (TW1) | **Winter:**  Dec12-Dec18 | Mean | 166.2 | 208.7 | 1.4 | 1.0 |
| Max | 644.1 | 886.6 | 15.6 | 1.2 |
| Min | 23.5 | 16.5 | 0.4 | 0.9 |
| window closed (TW2) | **Winter:**  Dec12-Dec18 | Mean | 167.7 | 208.7 | 1.4 | 1.0 |
| Max | 645.5 | 886.6 | 15.6 | 1.2 |
| Min | 23.9 | 16.5 | 0.4 | 0.9 |
| window open (TS1) | **Summer:**  Aug12-  Aug 18 | Mean | 19.2 | 26.1 | 0.5 | 1.0 |
| Max | 48.0 | 104.9 | 4.2 | 1.1 |
| Min | 4.7 | 1.0 | 0.2 | 0.9 |
| window closed (TS2) | **Summer:** Aug12-  Aug 18 | Mean | 19.2 | 26.1 | 0.5 | 1.0 |
| Max | 48.0 | 104.9 | 4.2 | 1.1 |
| Min | 4.4 | 1.0 | 0.2 | 0.9 |

Figure 4. *Outdoor and indoor* *transient airflow and transient PM2.5 pollutant simulation values during winter heating period.*

Figure 5. *Outdoor and indoor* *transient airflow and transient PM2.5 pollutant simulation during summer cooling period.*

Figure 6. *Outdoor and indoor* *transient airflow and transient NO2pollutant simulation during winter heating period.*

Figure 7. *Outdoor and indoor* *transient airflow and transient NO2pollutant simulation during summer cooling period.*

The indoor distributions of PM2.5 and NO2 in the condition of natural ventilation for different wind directions were simulated in the control area. Steady state weather data with four prevailing wind directions, namely 0° (N), 90°(E), 180° (S), and 270°(W), with a wind speed of 1 m/s, were set against the transient contaminant files for winter and summer periods. Since the window is located on the north side, the prevailing wind direction from the north (0°) and west (270°) drove the largest number of ambient PM2.5 particulates inside the control room during the heating period of the year. Conversely, the wind direction from the south (180°) gave the least effect due to the angular location of the simulated space (Figure 8). In the summer, the level of PM2.5 (weekly average 29.7 µg/m3) infiltrating through northern wind direction (0°) almost never lagged behind the external levels, and in some places exceeded them. This is because, while the level of PM2.5 is within reasonable limits during the summer (weekly average 26.5 µg/m3), the internal generation of suspended particles due to home cooking can exceed the concentration by several times (Figure 9). In the summer period the concentration of suspended particles inside the room were statistically significant (*r*(167) = .732, *p* < .001) according to the Pearson correlation for the direct direction of the wind from the north between the window open and closed scenarios for PM2.5 concentrations (Figure 9a).

a)

b)

c)

Figure 8. *Distributions of transient PM2.5 (a), NO2 (b), and mean PM2.5 (c) contaminants in the ambient and indoor air throughout the winter season under steady state airflow conditions at four prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W).*

a)

b)

Figure 9. *Outdoor and indoor* *steady state airflow at four prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W), and transient PM2.5 pollutant simulation during summer period for: a)-open window; b)-closed window.*

Figure 10 illustrates that a north prevailing wind direction contributes to the collection of a larger amount of NO2 pollutant inside the room during the summer period. There was *no* significant effect for indoor NO2 contaminants concentrations t(336) = -0.15, p = 0.8841, despite window open (*M* = 0.8, *SD* = 0.04) and window closed (*M* = 0.8, *SD* = 0.04) schedule conditions.

**4. Discussion and Conclusion**

Indoor PM2.5 and NO2 concentrations were simulated across different airflow combinations and window opening behaviour. Overall, evidence of seasonal differences in both studied pollutants was found. The average mass concentration of transient airflow PM2.5  particles (208.7 µg/m3) during the winter period predicted for an indoor environment exceeded the average daily WHO (2021) of 15 µg/m3 and Kazakhstan’s average daily Maximum Allowable Concentration of 35 µg/m3 guidelines by almost 1000% and 375% respectively. There are differences between WHO and Kazakhstan’s air quality standards. WHO uses daily and annual average recommended guidelines to assess the air quality, whereas in Kazakhstan, the values of one-time maximum allowable concentration (MAC) are being used (KAZHYDROMET 2021). Dangerous indoor PM2.5 concentrations in winter are attributed to high ambient pollution levels due to the proximity to the coal fired CHP plant and reduced winter air exchange rate (Assanov, Zapasnyi & Kerimray 2021).

Figure 10. *Ambient and indoor* *steady state airflow and transient NO2 pollutant simulation during summer period under prevailing wind directions: 0° (N), 90° (E), 180° (S), and 270° (W)*

The concentrations of NO2 across the different scenarios do not exceed WHO’s (25 µg/m3) and local (40 µg/m3) air quality guidelines (KAZHYDROMET 2021; WHO 2021); however, they are significantly above outdoor concentrations and are thus driven by indoor sources during both seasons. Also, there is a strong correlation on apartment location and infiltration within a building and season. The upper levels of the residential apartment building are more susceptible to higher concentrations of pollutants infiltrating from adjacent units during cold periods due to stack effect (Arku et al. 2015; Fabian et al. 2016). In addition, it was found that for the studied seasons, prevailing wind direction (Han et al. 2015) perpendicular to the opening, combined with the mechanical window opening during daytime, resulted in higher concentrations of indoor pollutants, especially PM2.5,which may contribute to serious health risks for the socially disadvantaged population in Almaty, Kazakhstan.

Overall, the study investigated the concentrations of transient pollutants indoors and outdoors and concluded that internal air quality should be considered when estimating the population's exposure level. In addition, the ventilation patterns for various prevailing wind conditions may significantly change the indoor exposure for a given outdoor pollution level. However, no significant relationship was found between window opening patterns for both studied periods. Future field monitoring of indoor pollutants will be carried out to calibrate the accuracy of the CONTAM model and provide data on existing indoor air quality levels in Kazakhstan's social housing stock. Investigations will also consider the specific details of the building, the closest outdoor obstacles and distance of pollutant source from the façade.

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