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ORIGINAL ARTICLE

# Transport processes in and above two-dimensional urban street canyons under different stratification conditions: results from numerical simulation

**Xian-Xiang Li · Rex E. Britter · Leslie K. Norford**

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**Abstract** Thermal stratification (neutral, unstable and stable) plays an important role in determining the transport processes in and above urban street canyons. This paper summarizes the recent findings of the effect of thermal stratification on the transport of momentum, heat, and pollutants in the two-dimensional (2D) urban street canyons in the skimming flow regime. Special attention is paid to the results from large-eddy simulations (LESs), while other experimental and numerical results are referred to when necessary. With increasing Richardson number, $Ri$, the drag coefficient of the 2D street canyon as felt by the overlying atmosphere decreases in a linear manner. Under neutral and stable stratification, a nearly constant drag coefficient of 0.02 is predicted by the LESs. Under unstable stratification, the turbulent pollutant transport is dominated by organized turbulent motions (ejections and sweeps), while under stable stratification, the unorganized turbulent motion (inward interactions) plays a more important role and the sweeps are inhibited. The unstable stratification condition also enhances the ejections of turbulent pollutant flux, especially at the leeward roof-level corner, where the ejections dominate the turbulent pollutant flux, outweighing the sweeps. With increasing $Ri$, both the heat (area active scalar source) and pollutant (line passive scalar source) transfer coefficients decrease towards a state where the transfer coefficients become zero at $Ri \approx 0.5$. It should be noted that, due to the limit of the 2D street canyon configuration discussed in this paper, great caution should be taken when generalising the conclusions drawn here.

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## 1 Introduction

With continuing urbanization around the world, research into the urban area has become so important and popular that Fernando et al. [1] proposed to initiate a new focus area—urban fluid mechanics (UFM)—tailored to research on issues relevant to urban flows (e.g., transport phenomena, air and water quality and health issues). Britter and Hanna [2] proposed to address the urban flow and dispersion at four scales: regional, city, neighborhood, and street. Belcher [3] reviewed the important dispersion processes at the street and neighborhood scales. As one of the basic elements of an urban area, the street canyon is ideal for urban research since, on one hand, it represents a simplified urban geometry; on the other hand, it can serve as a platform to synthesize the physical and chemical processes found in our environment. Actually we might consider there to be two basic elements to the urban layout; one where buildings protrude out from the underlying surface (reflecting, e.g., US and recent Asian urban development) and one where street canyons are impressed on to the underlying buildings (reflecting traditional European cities). Many would consider this far too simplistic but it does reflect very broad differences in style. The general interest in pollutant emission and subsequent dispersion in urban areas has also developed through concern about accidental and intentional release of harmful materials in urban areas. Urban areas are particular vulnerable with their concentrated population and congested layout.

In this paper we shall develop an overview of the depressed street canyon of unity aspect ratio with buoyancy effects, principally using computational techniques. There are, of course, substantial contributions to this general area of study from laboratory (water flume and wind tunnel, e.g., [4,5]) and from the direct use of RANS (Reynods-averaged Navier Stokes equations) models, though it is often difficult to extract results as detailed as those from LES (large-eddy simulation) modeling, from such studies. We might also consider whether it is an appropriate time to reconsider our overall view of pollutant dispersion in urban areas. Currently the basic model is that of pollutants being advected *through* a city and mixing/diluting with ambient air. But this slightly misses the point. The interaction is essentially one where the buildings act as pumps or fans that transport fresh air down towards the surface while expelling diluted air from the urban canopy. It is the *vertical* transfer that is of most interest and of most importance.

For an isolated building the flow will be forced around the buildings and also up and over the top of the buildings and down towards the base of the building [6]. A common concern here is that this may lead to unacceptable velocities near the base of buildings though this can be designed out. The reverse of this problem is of great consequence, particularly in hot countries. Here the designer may want to provide some relief from medium to high temperatures by providing increased ventilation near the building base and, possibly, in the void space under the building. Similarly the interaction of flows between and among the buildings (of different heights) may also aid in the ventilation of the regions between buildings [7].

Of course this also introduces the interaction between the velocity field within urban areas and the thermal field; the thermal field due to the incident radiation, anthropogenic sources and more generally the storage and release of heat from the built city and local water bodies.

A further goal of building design is the ventilation of the regions between buildings [8] in order to ensure that air quality levels are not exceeded; increased wind velocities will lead to mixing and dilution of air pollutants.

The interpretation of the flow will differ depending on the type of building morphology. Here we restrict our attention to the “street canyon” type morphology.

It is interesting to reflect on the change in the tools available for studying the urban environment. Experimental techniques at global, field and laboratory scales have developed markedly to the point where totally pervasive environmental sensors and sensing can be seen to be a real option. Mathematical modelling, again at global, field or laboratory scale is now available both individually and in many multi-scale formats. Additionally the effort to produce operational, but also simple (appropriate) and transparent modelling tools advances rapidly. The computational fluid dynamics (CFD) technique in its many forms provides a wide range of technical options for investigation [9]. While RANS based models still have a role to play, the use of LES modelling can explicitly resolve atmospheric flows of various scales ranging from an individual roughness element to an entire boundary layer [10]. Various urban flow and dispersion models have been developed based on CFD to simulate the complicated wind pattern and pollutant transport [9]. The success of these models in predicting street-canyon ventilation depends on physically accurate descriptions of turbulence and dispersion within and above the street, particularly in light of the suggestion of Louka et al. [11] that ventilation is mediated by inherently intermittent flushing events driven by instabilities in the shear layer. The results from these models are usually in need of validation against laboratory or field measurements.

It has been suggested that, in a fluid-mechanical context, one of the most pressing problems was the treatment of atmospheric stability in urban areas [2]. Ever since then, many numerical studies have been conducted to investigate the thermal effect in urban areas. Here we address the effects due to thermal releases in the urban canopy.

The focus of this paper is the buoyancy effect on the flow and pollutant transport in two-dimensional (2D) urban street canyons. In passing we note that the effects of buoyancy are liable to be more severe in the 2D problem than in the three-dimensional (3D) one. This is a result of the more substantial area for entrainment into the 2D plume. For comparison, the characteristics of flow and pollutant transport in urban street canyons under isothermal conditions will first be summarized in Sect. 3 before the case with buoyancy effects is presented in Sect. 4. The work discussed is mainly carried out by LES, but some experiments and numerical work by RANS models will also be referred to when necessary.

## 2 Flow and transport at street scale

Most people in most cities will find themselves living and working in street canyons and breathing the air there. They will often be using energy for heating or cooling their homes (and their environments). In a sense the street canyon, where we live, is where the large scale and the small scale processes overlap. A “street canyon” generally refers to a relatively narrow street in between buildings that line up continuously along both sides. As a basic geometric unit of urban areas it is also bounded by the ground surface at the bottom and the roof level at the top. It has a distinct climate where micro-scale meteorological processes dominate [12] and the air ventilation and pollutant removal are often treated solely as being through the roof level. The most important features of street-canyon micro-climate are the wind-induced flow patterns, such as air recirculation inside and the unsteady flapping at the

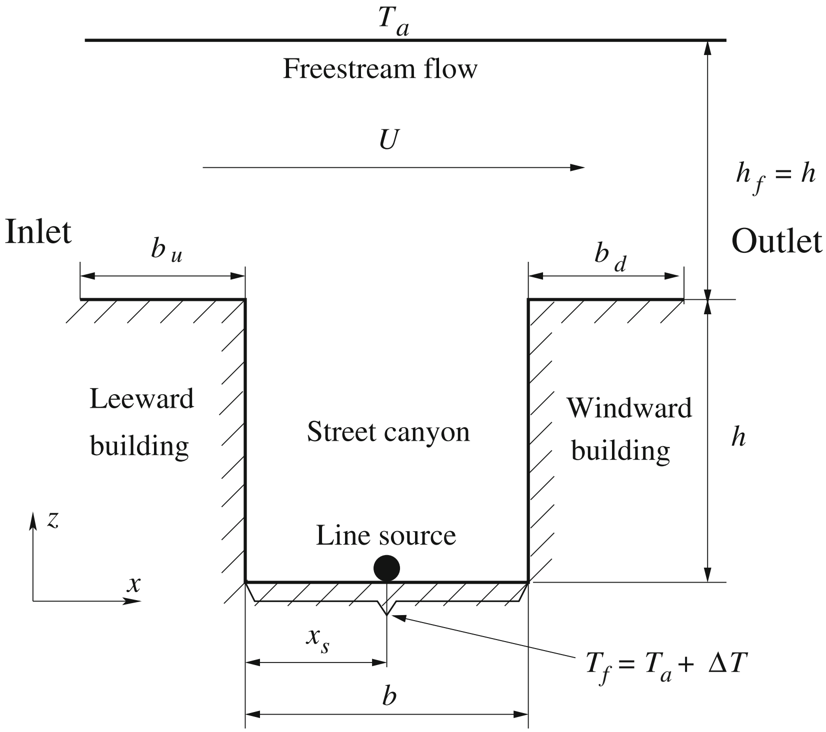

**Fig. 1** Schematic diagram of computational domain for the flow and pollutant transport in a street canyon with ground heating. The origin is located at the left ground corner of the street. Here $h$ is the building height, $b$ is the street width, $h_f$ is the height of freestream flow, $b_u$ and $b_d$ are the width of the upstream and downstream buildings, $x_s$ is the distance of line pollutant source from the upstream wall, $T_f$ and $T_a$ are the temperature of the street and the ambient air, and $U$ is the freestream velocity

roof level. These unique micro-scale meteorological processes not only affect the local air quality but also the comfort of the city inhabitants [13].

The 2D or quasi-2D street canyon (quasi-2D refers to some laboratory or numerical configuration of 3D urban street canyons with the spanwise direction homogeneous or infinitely long) is a drastic simplification of real urban geometry, but it is necessary in order to clarify the basic governing mechanisms of the phenomena [14–16]. Oke [12] classified the flow pattern in and across 2D street canyons into three characteristic regimes, i.e., isolated roughness, wake interference and skimming flow, according to the building-height-to-street-width (aspect) ratio $h/b$ (see Fig. 1 for the schematic of a typical setting for street canyon simulation). The last of these, skimming flow, is when the flow separates and reattaches at elevation above the ground level. This occurs around roughly $h/b > 0.67$, and is the major flow pattern found in dense urban areas, and thus a widely studied subject in the literature.

There is now sufficient evidence to confirm the argument of Louka et al. [11] that the conventional skimming flow picture of a steady canyon recirculation should be revised in a sense that the driving shear layer is unsteady due to shedding of Kelvin–Helmholtz waves (see Fig. 2), which renders also the canyon recirculation highly intermittent. Cui et al. [17] attributed the dominant time scale in the shear layer to eddies that would typically be produced by Kelvin–Helmholtz instabilities. Of course the driving shear layer will be unstable and will produce mixing between the fluid above and the fluid within the canyon whatever

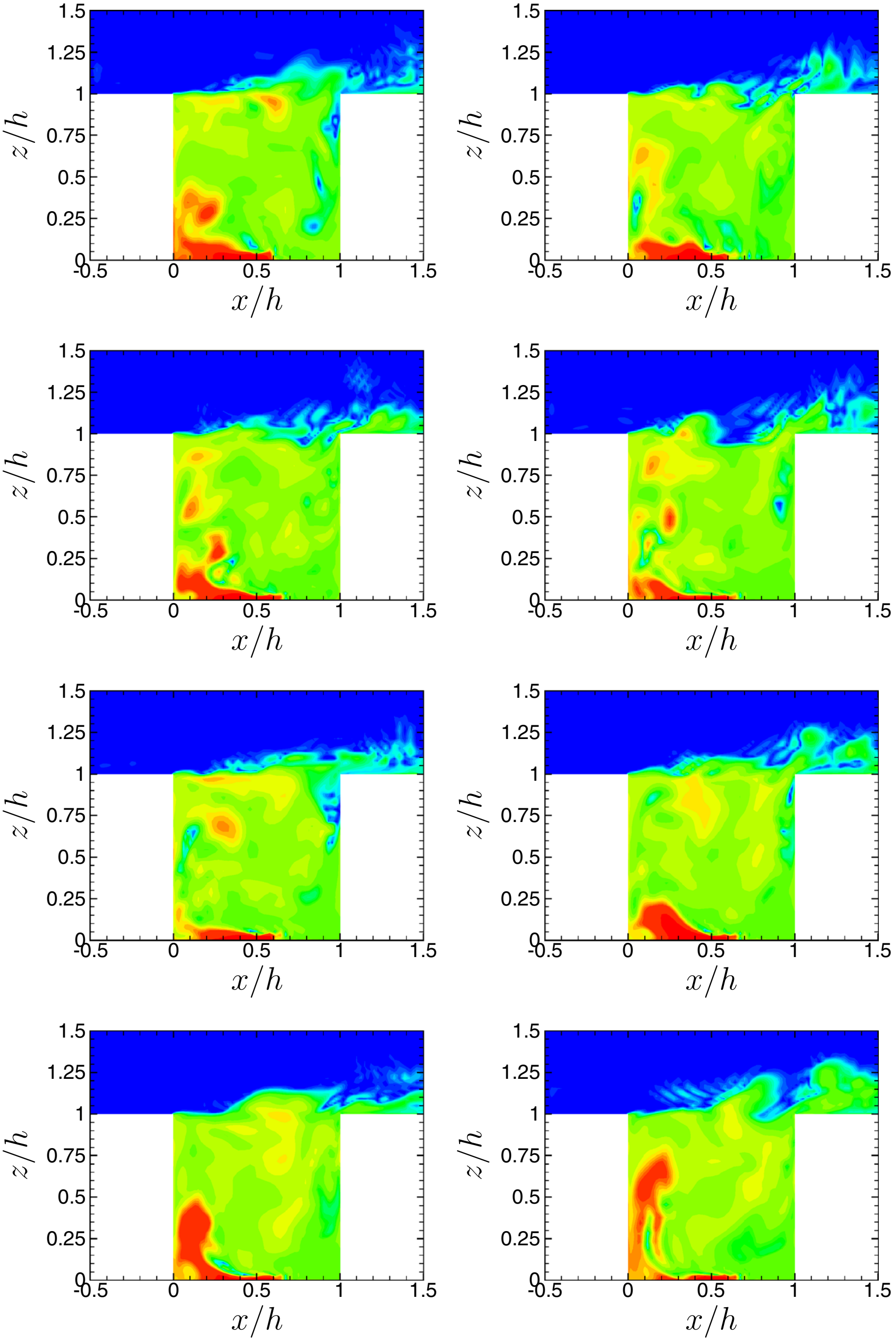

**Fig. 2** *Snapshots* of instantaneous pollutant concentration in a 2D street canyon of $h/b = 1$ as simulated by our LES. The freestream wind blows from *left to right*. The time increment between each figure (*from left to right*, *from top to bottom*) is $20h/U$. *Red* and *blue* colors represent high and low concentration, respectively. A Kelvin–Helmholtz instability at the roof level, fresh air entrainment along the windward wall, and pollutant transport along the leeward wall are clearly seen

the nature of the instability. The water-channel visualization by Huq et al. [16] suggested that there was no Kelvin–Helmholtz instability in the street canyons for $h/b = 0.64$ and 1.92, possibly due to their geometrical arrangement of the building models being 3D rather than nominally 2D. Their observations also revealed that, due to this 3D nature of the flow at the rooftop level, the angles of spread of the shear layer are smaller than that observed by Brown and Roshko [18] for a 2D shear layer. A recent water channel experiment [19] showed that in real 3D rectangular arrays of cubical obstacles, there is a net flow along the canyon perpendicular to the main stream (outer flow), which is intensified when the central cube is replaced by one with double height. This is an effect usually not observed in laboratory experiments, mainly because of the 2D symmetry of structures employed.

Of course the important message here is that urban morphology is often very complex, as is the flow over and through it. It must be remembered that simple descriptions of idealized cases are important but they will have limitations. For an "ideal" street canyon the upstream and downstream heights are equal. If we ignore the complexity of the on-coming boundary layer there will be an unstable shear layer at the top of the canyon producing a mixed layer that will transport material out of, and across, the canyon. The fluid removed from the canyon must be balanced by an inflow into the canyon and this occurs near the downstream edge of the canyon. Thus a circulation is set up in the canyon with possibly small separation regions near the bottom corners. Impingement of part of the flow on to the downstream canyon face leads to some flow down into the canyon and some to continue downwind. This mass flow arrangement seems clear and reasonable and can be clarified by more precise application of mass, momentum and energy equations in integral or differential form. In summary then, for 2D street canyon in skimming flow regime, the mean flow has the following characteristics:

- there is a mass flux into and out of canyon with a net mass flux of zero;
- a force on the canyon walls, or on finer structures ("street furniture") within the canyon will produce a sink for the streamwise momentum flux;
- this sink for streamwise momentum flux will be matched by a source of streamwise momentum flux arising from the different streamwise velocity of the flows entering and leaving the street canyon.

Changing the aspect ratio from 1.0 to 0.5 and then to 2.0 we observe very substantial changes in the flow pattern. The single vortex converts into two, either side by side for an aspect ratio of 0.5 or one above the other for an aspect ratio of 2.0. The former case is due to reattachment of the separated shear layer within the canyon [20]. Generally these observations are understood except perhaps that some controversy exists in the literature regarding the number of vortices that form when the aspect ratio is large (more than 2.0) though this may also be a Reynolds number effect [21].

The flow structure inside the street canyon is of crucial importance for the dispersion of the pollutants emitted from street level, particularly vehicular exhausts. Britter and Hanna [2] summarized the evidence from several urban dispersion field studies, pointing out that the concentration level in urban areas is determined by two opposing factors: increased turbulence levels produce greater dispersion and hence lower concentrations; but reduction in advection velocity within the canopy tends to increase concentrations. They conjectured that, as surface roughness is increased, the ground level concentration may decrease to a minimum before increasing, possibly attaining levels equal to or exceeding that for an unobstructed case.

Usually there are two geometrical types of sources of scalars in a street canyon: First is the line source, with fluid injected directly into the atmosphere (to ideally reflect vehicle pollutants emitted into the street canyon), and second the area source on an urban facet (e.g. water vapor evaporated from rainfall on the street) [22]. For the first type of source, the emission rate (or flux) is usually used to characterize its strength, while for the second type of source, the emission rate is often unknown due to its nature of an evaporation-driven process in the vicinity of the source; instead, the concentration of the scalar can be obtained. One of the major applications of the second type of source is to assess the latent heat flux inside a street canyon in order to understand better the mechanisms governing the climate inside the urban canopy layer.

Street intersections (or junctions) are a second basic element of urban geometry that are critical in dispersion [23]. There are two generic intersections: a four-way intersection, where two simple streets cross at 90°, and a T-junction, where two simple streets meet at 90° and the entrance street terminates. Boddy et al. [24] identified the T-junction as a strong force for lateral and vertical dispersion. The incoming flow emerges along the entrance street as a jet. This jet then impinges on the downwind wall, leading to a recirculation region where the centreline of the entrance street impinges upon the downwind wall [3]. Kastner-Klein et al. [25] measured the effects of a four-way junction on the flow in a simple street and identified its circulation characteristics. Perpendicular flow over a simple street generates a mixing circulation, with its axis aligned horizontally along the street. At a four-way junction the jet that emerges from the entrance street generates a mixing circulation, with its axis aligned vertically [3]. Dispersion and exchanges of scalar are enhanced at street intersections. Robins et al. [26] found that pollution emitted in one street can penetrate far into another at an intersection. Minor departures from symmetry were found to result in large differences in the exchanges. Carpentieri et al. [27], making wind-tunnel measurements at an asymmetric intersection, observed complex 3D effects that enhanced the interaction of the canopy flow with the overlying flow.

Many important aspects will not be covered in this paper. Traffic induced mechanical turbulence is an important source of turbulence in urban street canyons [2,28], but is out of the scope of this paper. Roof geometry effects such as pitched roofs or asymmetric canyons (step-up or step-down notch) will also not be addressed here. Many previous investigations [25,29–31] have demonstrated a significant influence of roof geometry on canyon circulation and the associated integral statistics of the flow. The shear layer at roof level is elevated and modified so that the canyon vortex may not form at all [25]. However, field studies [32] in a real pitched roof street canyon did detect a canyon recirculation. This suggests that the formation of a strong canyon vortex may depend on the details of any particular scenario.

## 3 Flow and dispersion under neutral stratification conditions

Under neutral stratification, when the wind is perpendicular to the street axis, the flow in a 2D street canyon is mainly characterized by primary recirculations inside the street canyon and a skimming flow above, with a roof-top shear layer in-between [20]. Louka et al. [11] showed that the position of this roof top shear layer intermittently flaps up and down.

The turbulent transfer between a 2D street canyon and the overlying atmospheric flow is an unsteady and highly intermittent process. The energy for this process is provided by the mean kinetic energy of the external flow, whose forcing action on the canyon flow is regulated by the dynamics of a region of high shear at the interface between the two. Within the resulting shear layer Kelvin–Helmholtz instabilities arise and generate vortices that grow while they are advected downstream from the upwind corner (see Fig. 2; also refer to [33]).

The unsteady condition of the flow results in a flapping motion of the shear layer and a subsequent intermittent inflow of turbulent structures into the canyon that induces the bulk transfer between the canyon and the external flow [34].

Thus the flow in and above street canyons can be divided into three parts: (1) external flow; (2) cavity shear layer; and (3) cavity flow. Several efforts to scale the flow in and above street canyons have been attempted. Huq et al. [16] used the difference between velocities across the shear layer, $\Delta U$, to fit the non-dimensional mean velocity profile of a street canyon of $h/b = 1.92$, and found the profile fits well to the hyperbolic tangent form [35]. However, the study of Salizzoni et al. [36] showed that it is not possible to use a single scaling parameter to scale the flow in all the three parts of street canyons. This is not surprising as the three parts of street canyon flows reflect quite different fluid mechanical phenomena and these need not scale in the same manner.

The pollutant emitted from street-level sources (e.g., from vehicles) generally follows the primary recirculations in the street canyon. High pollutant concentration and high variance were found near the buildings where wind flowed upward; of course this is a direct consequence of the pollutant sources being low down within the canyon. Large gradients of pollutant concentration and variance were also observed at the interfaces between the primary recirculations and the shear layer. Detailed analyses of the concentration budget showed that the advection terms were responsible for pollutant redistribution within primary recirculations, while the turbulent transport terms were responsible for pollutant penetration between primary recirculations as well as pollutant removal from the street canyon [21].

The concentration of a passive pollutant in a 2D street canyon is governed by three main mechanisms: the source input rate, the advection-diffusion processes inside the canyon, and the transfer at the roof level of the canyon [33]. Of the three mechanisms, the last one has attracted the most research concerns due to its intimate relationship with urban air quality. There is a consensus that turbulent motions dominate the pollutant removal in the skimming flow regime. A quadrant analysis [37] is usually adopted to quantify the contribution of each quadrant to the turbulent pollutant flux $\overline{w'c'}$, where $w'$ and $c'$ are the fluctuation of vertical velocity and pollutant concentration from their temporal average (denoted by the overbar), respectively. The first quadrant ($w' > 0$, $c' > 0$) is called ejections, which are the "ejection" of slow-moving fluid from the urban canyon into the shear layer above, while the third quadrant ($w' < 0$, $c' < 0$) is called sweeps, which are the replacement of ejected fluid with relatively high-speed fluid from outside the street canyon. Please note that the definitions of ejections and sweeps here for turbulent pollutant flux are different from those for momentum flux due to the different transport processes of pollutant and momentum. Quadrant analysis of turbulent pollutant fluxes have shown that the ejections and sweeps dominate while sweeps contribute slightly more than ejections near the roof level [38], while Michioka et al. [39] indicated that a large amount of pollutant is removed from the canyon by ejection due to the large-scale coherent structures. The turbulent intensity of the approaching flow could also directly influence pollutant removal from street canyons, as demonstrated in wind-tunnel experiments [34] and numerically [40]. The average pollutant concentration within the street canyon decreases as the friction velocity, $u_*$, of the approaching turbulent flow increases [34,41]. This is a direct result of the friction velocity being a measure of the mixing processes and of the bulk exchange of fluid near the top of the street canyon that will reduce the concentrations within the street canyon.

Michioka et al. [39] showed that the coherent structures close to the plane of the roof strongly affect pollutant removal from the street canyon. Therefore, changes in turbulent structures upwind of a street canyon where pollutants are emitted may cause different mechanisms of pollutant removal (i.e., removal majorly by the mean or turbulent pollutant flux) when the street canyon geometry remains the same [41]. They also demonstrated that the vertical scalar transport from a 2D square cavity is enhanced below the passage of low-momentum streaks. Large outer-layer eddies are found to contribute to the Reynolds stress in the outer layer, and also to the turbulent transfer of scalars such as heat [42,43].

Very similar arguments and results will generally be applicable to similar thermal arrangements if temperature is treated as passive scalar (e.g., when the buoyancy effect is negligible). That is, the arguments above will reflect the temperature development for any given thermal source arrangement. The scalar temperature is advected by the mean flow and diluted by the turbulence. Of course the above is true for smooth wall problems but not necessarily for walls with large roughness. For flows with large surface roughness the analogy between heat and momentum breaks down. Momentum may be transferred by normal and shear stresses but there is no thermal analogy to the forces arising from the variation of pressure around obstacles particularly when the flow separates at large Reynolds numbers.

In summary, we might interpret the flow as one in which a mixing process at the canyon top produces an exchange of mass, pollutant, heat and momentum across the canyon, thereby producing relevant fluxes.

## 4 Flow and dispersion under unstable/stable stratifications

When the thermal effects are substantial (due to solar radiation, the release of stored heat, and anthropogenic heat for example) they can have a profound impact on the thermal field itself, the flow field and therefore the pollutant dispersion in street canyons, as demonstrated by many previous studies [44–48]. The main parameter characterizing the stability is the bulk Richardson number

$$Ri = \alpha g h \Delta T / U^2, \tag{1}$$

where $\alpha$ is the thermal expansion coefficient, $g$ is the gravitational acceleration, $\Delta T$ is the temperature difference between the urban facet and the approaching air, $U$ is the reference velocity, and $h$ is the building height. Negative $Ri$ indicates unstable stratification and positive $Ri$ indicates stable stratification. There are many different types of Richardson number (e.g., bulk or integral, gradient, flux), all with different applications, interpretations and intentions (see, e.g., [49,50]). The bulk Richardson number of Eq. (1) highlights the importance of the group of variables in the form of one dimensionless variable rather than the individual variables themselves. As the bulk Richardson number is made larger the entrainment (of which there are various types) or mixing of the fluids decreases to very small values, with consequent effects on flow. Note that the approach underlying Eq. (1) has been based on using $\Delta T$ as an independent variable and, for example, the heat flux (local or integral) as the dependent variable. This approach is one option. Alternatively the flow may be thought of as one where the heat flux through the canyon walls is specified as the independent variable and the resulting wall temperatures or, possibly, their averaged value are the dependent variables. Hence another Richardson number based on surface heat flux $\overline{w'T'}$ can be defined as

$$Ri_f = \alpha g h \overline{w'T'} / U^3, \tag{2}$$

where $T'$ is the fluctuation part of the surface temperature. Obviously some care is needed in interpreting these different approaches. It is of consequence to know when thermal and mechanical effects are both important and when only one or the other are of influence.

The presence of a thin thermal layer close to the walls is an important characteristic of the micro-environment around the buildings and is difficult to be accurately represented by CFD codes at modest cost, particularly when many scenarios are required as, say, part of a design process [51]. It has been argued that any thermal effect on flow and dispersion shown in laboratory experiment and computational studies is far less evident in field measurements [51] probably because, in the field, the physical width of the free convective boundary layer on the heated wall is small compared with the scale of the mechanically driven motion, which is on the street scale. Of course when the external flow is very weak these thermal effects are of greater consequence [2]. It is also likely that the thin thermal layer close to the walls is not reflecting the reality of real, complex walls whose operational characteristics are not captured by conventional rough wall descriptions. Therefore, extra care should be taken when dealing with this issue even when the geometrical configurations are simple.

Due to the existence of such a thin near-wall thermal layer, it is very challenging to study the flow and heat transfer at realistic Reynolds number using LES. Resolving such thermal layers is too expensive while appropriate thermal wall models are not yet available. Therefore, in the LESs found in the literature, many compromises have to be made: e.g., the building surfaces and ground are assumed to be adiabatic or at fixed temperature; local heat transfer from building and ground surfaces is assumed less important than larger scale heat transfer and thus ignored [52].

Solazzo and Britter [53] argued that the buoyancy effects of building-wall heating by solar radiation are confined to the near-wall region, and their contribution to the overall flow is negligible. However, a simulation of a selected area in downtown Phoenix performed by Fernando et al. [4] showed that buoyancy effects were appreciable in the middle of the street canyon; but near the ground (say $z < 10\,\mathrm{m}$) the buoyancy effects are hardly felt due to shear production. This also seems at odds with Louka et al. [51] observations and conclusions that a thin thermal layer develops locally within a few 10's centimetres from the heated wall. The arguments of Solazzo and Britter [53] were influenced by Louka et al. [11] observations but they considered the flow local to the buildings rather than the flow on the overall scale of a building complex.

### 4.1 Flow, turbulence and scalar field

Li et al. [54,55] have performed LES studies of flow and pollutant dispersion in street canyons of $h/b = 0.5$, 1, and 2 with ground heating ($Ri$ ranging from $-0.5$ to $-2.9$), where "ground heating" is the term used for heating or cooling of the air near the ground by heat transfer to or from the ground. Their results showed that the ground heating significantly enhanced the mean flow, turbulence, and turbulent pollutant flux inside street canyons, but weakened the shear layer at the roof level. Consequently the ground heating may seriously inhibit the growth of the Kelvin–Helmholtz instability developed in that shear layer in the isothermal case (see Fig. 2). With ground heating, the flow in the street canyon of $h/b = 0.5$ can change from wake interference to skimming flow regime, while the two vertically-aligned vortices in the street canyon of $h/b = 2$ can merge into one large vortex [55].

For street canyons of $h/b = 0.5$, 1, and 2 under ground heating ($Ri$ ranging from $-0.5$ to $-2.9$) with a line source located at the ground level, the temperature distribution inside the street canyons is not quite as sensitive to $Ri$ compared with the distribution of pollutant. With decreasing $Ri$ (increasing instability), the pollutant removal from the street canyon is greatly enhanced, while the non-dimensional temperature difference (the temperature difference between the air inside the street canyon and approaching air, non-dimensionalized by $\Delta T$) inside the street canyon only increases slightly [55]. The important difference between "no-

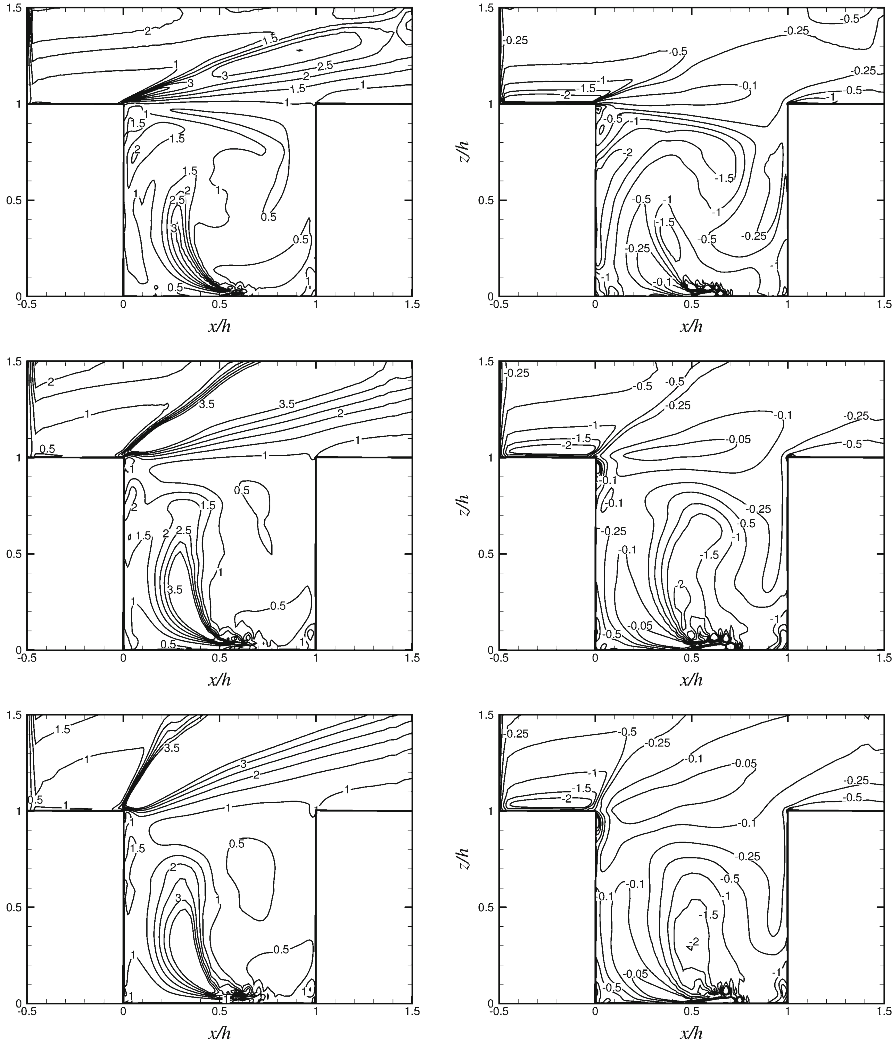

**Fig. 3** Quadrant analysis of pollutant flux in an urban street canyon of $h/b = 1$ under different thermal stratifications, as computed by our LES. *Left* ratio of the contribution from ejections to that from sweeps; *Right* the ratio of the unorganised contributions to organized contributions of turbulent pollutant flux. From *top to bottom* the Richardson number $Ri = 0$, $-0.6$ and $-2.4$

heat-flux” or “adiabatic” and “fixed-temperature” boundary conditions for temperature at solid walls has also been demonstrated [55]. In the case with adiabatic boundary conditions, the non-dimensional temperature difference inside the street canyon is much higher. due to the fact that the adiabatic walls will prevent any heat loss into the buildings and the ground.

The quadrant analysis (see Sect. 3 for definitions) of turbulent pollutant flux under neutral and unstable stratifications (with ground heating) in a street canyon of $h/b = 1$ is presented in Fig. 3 (left panel). The line pollutant source is located in the middle of the ground level. It is evident that near the leeward wall the ejections dominate, while near the downward wall the sweeps dominate, corresponding to the updraft of polluted air and the downdraft of fresh air, respectively. With increased ground heating the contribution from sweeps becomes higher than that from ejections at the roof level, due to the enhanced downdraft and mass transfer there. Above the roof level, ejections dominate in all the cases, which is consistent with the field measurement of the urban roughness sublayer turbulence [56]. If we denote the contribution of the $i$-th quadrant to $\overline{w'c'}$ as $S_i$, the ratio of unorganized contributions (from inward and outward interactions) to organized contributions (from ejections and sweeps) [57], i.e.,

$$Ex = \frac{S_2 + S_4}{S_1 + S_3} \tag{3}$$

is also shown in Fig. 3 (right panel). The unorganized contribution transports pollutant downward, which is counter to the overall upward flux of pollutant. Therefore a higher $Ex$ (note that $Ex \leq 0$) means higher efficiency of scalar transfer by turbulence. Near the line source, the transfer is the least efficient, while in the plume of the line source, the transfer is quite efficient. At the roof level with a small shift to the leeward corner, $Ex$ reaches its maximum. This maximum increases significantly from $-0.1$ to $-0.05$ with the increasing heating intensity. It is interesting to note that the ground heating increases the transfer efficiency in the plume of the line source, but decreases dramatically the efficiency near the line source.

For a street canyon of $h/b = 0.5$, when ground heating is introduced ($Ri$ ranging from $-0.9$ to $-2.9$), along the roof level, both the mean flow and turbulence contribute to pollutant removal [55], which is consistent with Kang et al. [58], while under neutral stratification condition, the mean flow contributes little to pollutant removal.

Cai [22,59] investigated the cases of upstream and downstream wall heating ($Ri$ ranging from $-0.14$ to $-2.14$) in urban street canyons of $h/b = 1$ using LES. Two idealized cases were studied: (1) the roof and the upstream wall are heated (‘assisting case’); and (2) the roof and the downstream wall are heated (‘opposing case’). These cases can be observed in reality when either the downstream or upstream wall is shaded due to the angle of solar radiation at different time during daytime. For the assisting case, the mean flow pattern is nearly symmetric; the primary vortex extends to above the roof level; and the primary vortex is strengthened by the wall heating. For opposing cases, the mean flow patterns are fairly asymmetric; the primary vortex intensity is significantly suppressed by the downstream-wall heating, a secondary vortex is assisted by the downstream-wall heating, and its size does not always grow monotonically with wall heating; the interaction between the primary vortex and the thermally driven updrafts generates a significant amount of turbulent kinetic energy (TKE); and an unsteady penetrating narrow updraft zone appears occasionally along the heated wall. For the street-released scalar in the opposing cases, the concentration fluctuations in the street canyon relative to the mean concentration can reach 50 % and in general they are much larger than those for the assisting cases that are in the range of 25–30 %. The assisting cases are favorable to ventilating the scalars from both walls, whereas the opposing conditions are only favorable to the ventilation of the downstream-wall released scalar. These studies also demonstrate that the sensible heat flux and canyon-air temperature are significantly sensitive to the thermal roughness length of the building surfaces, $z_{0T}$, which is generally much smaller than the roughness length for momentum, $z_0$ [60]. It is thus vital to choose an appropriate value for this parameter and carefully designed laboratory or field experiments for quantifying $z_{0T}$ for various urban surfaces are required.

Few studies have investigated the effect of stable stratification on these flows. Uehara et al. [47] measured flow and turbulence in a cubic array under unstable, neutral, and stable thermal stability in a wind tunnel. Cheng and Liu [61] performed an LES of flow and dispersion in urban street canyons under unstable, neutral, and stable stratification conditions. The mean wind speed in the street canyon is enhanced under unstable conditions but is weakened under stable conditions. Under stable conditions ($Ri = 0.18$ and 0.35), a layer of stagnant air is formed at the ground level and the pollutants are trapped there. As a result, the pollutant retention time in the street canyon increases with increasing $Ri$. We also performed an LES of street canyon flow under stable stratifications by inverting the direction of $g$. For $Ri = 0.19$ and 0.37 our results of flow and pollutant are quite similar to those reported in Cheng and Liu [61]. Recently, Xie et al. [52] investigated the flow and dispersion in an array of staggered cubes with an approaching flow of different thermal stratifications. Under stable stratification ($Ri = 0.2$), the size of the circulation formed in front of a cube is smaller than that under unstable stratification ($Ri = -0.2$). Their results also indicated that the effect of the stable stratification on flows over staggered cubes is quite different from that for street canyons (e.g., [51]), possibly due to the flows being highly 3D and the scales of eddies within and immediately above the canopy being dominated by the cube size. This conclusion emphasizes that the real flow is usually 3D and any generalization from the 2D street canyon study should be cautious.

### 4.2 Scalar transfer

The scalar fluxes from the street canyon are important quantities for the transfer processes between the urban canopy layer and the overlying atmosphere. Mesoscale models or models of urban energy balance require the parameterization of these transfer processes. Therefore, many laboratory and numerical studies have been performed to quantify these processes. If the spatio-temporal average of the scalar flux at the roof level is $F$ and the "strength" of the source is $C_s$ (this can be temperature for heat flux and concentration for pollutant flux), and the ambient (background) "strength" of the scalar is assumed to be zero, the transfer coefficient is then defined as [38,62,63]

$$\Phi = F/(UC_s). \tag{4}$$

When the source "strength" is expressed as a flux $F_s$, the transfer coefficient is then

$$\Phi = F/F_s. \tag{5}$$

The exchange velocity is defined as

$$w_T = F/C_s. \tag{6}$$

When $F$ is heat flux and $C_s$ is surface temperature, $\Phi$ is often referred to as the Stanton number, $St$, in the engineering community. Note that here the transfer coefficient is defined for either the street canyon as a whole or for a specific facet of the street canyon (e.g., walls, street, and roofs).

Cai [22] showed that the exchange velocity of a scalar between the street canyon air and the urban boundary layer can be one order of magnitude larger than the exchange velocity between a facet and the urban boundary layer, which indicates that the resistance of a facet-released scalar is dominated by the near-facet processes. Both wind tunnel [62] and LES [63] studies have shown that the transfer coefficient of a scalar depends on the urban geometry (e.g., $h/b$) and the location of sources. The transfer coefficient and exchange velocity are also affected by the atmospheric stability. In the downstream-wall and upstream-wall heating cases studied by Cai [22], the exchange velocities between the urban air and the urban boundary layer linearly increase with $\Delta T$.

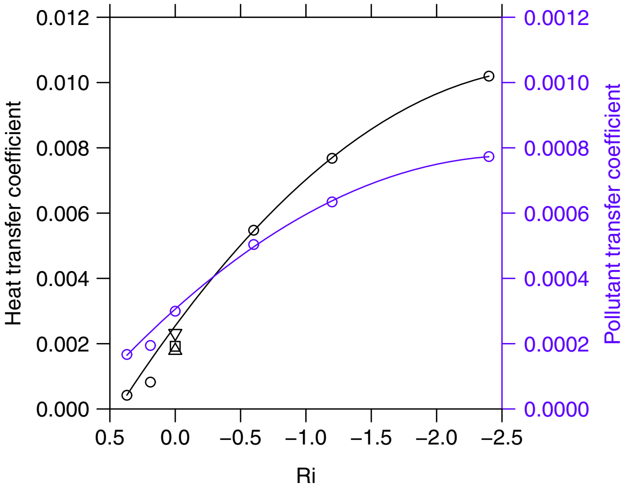

**Fig. 4** The transfer coefficients of heat (area active scalar source) and pollutant (line passive scalar source) of the street canyon of $h/b = 1$ as a function of $Ri$, as computed by our LES. The sources are both located at the street level as shown in Fig. 1. The *solid lines* are least square fits of the coefficients. Also shown are the transfer coefficient of a scalar (area source) under neutral stratification ($Ri = 0$) from wind tunnel [62]: *square*; LES [63]: *triangle up*; and LES [38]: *triangle down*

Figure 4 summarizes the relationships between the transfer coefficients of heat (area source) and pollutant (line source) and $Ri$ from our LES studies. Both scalars are emitted from the street ground level. It should be noted that the heat in these studies is an active scalar that can dynamically interact with the flow field. Both the heat and pollutant transfer coefficients increase with decreasing $Ri$. It is interesting that the results show, with increasing $Ri$ (decreasing instability), the curves decrease systematically towards a state where the transfer coefficients become zero. Furthermore this occurs when $Ri$ is around 0.5 (which corresponds to a 2 °C temperature difference between the ambient air and the street ground at a full scale of $h = 40\,\mathrm{m}$ and $U = 5\,\mathrm{ms}^{-1}$), a value typical of stable conditions under which turbulence and transfer processes often collapse. However, it should be noted that, due to the limited number of data points, the extrapolation to a zero transfer coefficient may not be true and therefore misleading. The conclusion here therefore should be used cautiously.

The effect of buoyancy in a 2D street canyon of $h/b = 1$ from the above studies can be summarized as follows:

- With increasing $Ri$, the drag coefficient of the 2D street canyon as felt by the overlying atmosphere, $C_D = F_D/(0.5\rho U^2 A_{frontal}) = 2\Delta p/U^2$, decreases in a somewhat linear manner (see Fig. 5). Here, $F_D$ is the drag force the street canyon exerts on the overlying atmosphere, $\rho$ is the air density, $A_{frontal}$ is the frontal area of the street canyon in the wind direction, $\Delta p$ is the kinematic pressure difference between the upstream and downstream boundaries, and $U$ is the freestream velocity. With increasing $h/b$, the drag coefficient decreases. There is a strong correlation between $Ri$ of the flow and $C_D$. The data show a nearly constant $C_D$ of around 0.02 for the stable and neutral cases. Again, caution should be taken when using this conclusion from curve fitting due to limited data availability. The increase of $C_D$ with the increasingly negative $Ri$ (increasing instability) is in line with [64, p. 225]. The reason is that increasing instability will enhance vertical mixing and hence the momentum flux $\overline{u'w'}$, which can also be viewed as Reynolds stress and is the major

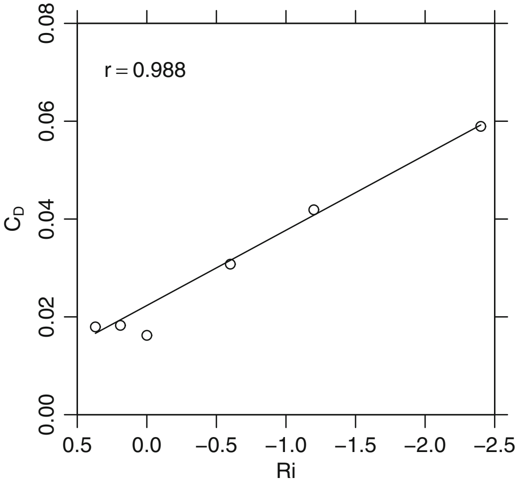

**Fig. 5** The drag coefficient $C_D$ of the street canyon of $h/b = 1$ as a function of $Ri$, as computed by our LES. The solid line is a least square linear fit of the points and $r$ is the correlation coefficient of the fit

resistance to the overlying atmosphere. Thus, the drag force exerted on the approaching air will become larger with more negative $Ri$.

- Under unstable stratification the turbulent pollutant transport is dominated by organized turbulent motions (ejections and sweeps), while under stable stratification the unorganized turbulent motion (inward interactions) plays a more important role and the sweeps are inhibited.
- Under unstable stratification the ejection of turbulent pollutant flux is enhanced compared with that in the neutral stratification case, especially at the leeward roof-level corner, where the ejections outweigh sweeps.

Due to the difference in the sources of momentum and heat/pollutant fluxes, the transport processes of these fluxes inside the urban street canyon are dissimilar [65]. The momentum flux is mainly attributed to form drag, which is greatest at the roof level and smallest at the ground. On the other hand, the profile of turbulent heat/pollutant flux can vary depending on the location of the source. For the cases with flux/pollutant source at the ground level, the flux values usually have two maxima: near the source and at the roof level (see [54,55]). However, above the roof level, the transport processes of these fluxes are quite similar under near-neutral conditions [65].

## 5 Perspectives

This paper summarizes some characteristics of two-dimensional street-scale flow and dispersion under different thermal stratifications as learned from numerical simulations especially LES. It has been shown that the stability condition greatly impacts the various aspect of urban flow and dispersion, particularly, the exchange of mass, momentum, heat, and pollutants between the street canyon and the overlying roughness surface layer. Due to the very specific cases studied in this paper, some caution should be taken when generalizing the conclusions drawn.

While various laboratory and field experiments of the urban flow and dispersion have been conducted, which help in formulating our understanding of this important topic, relatively less numerical studies, especially LESs, have been performed to fill the gap of understanding. Many of the most detailed numerical studies have been limited to flow perpendicular to a group of regular obstacles [66]. Some recent numerical studies have attempted to address this lack of realistic incoming wind and turbulence (e.g., [67,68]). With the development of computational resources, more sophisticated CFD models (either RANS or LES), e.g., a 3D version of the model from Ca et al. [45] with complete treatment of solar radiation, heat transfer and shadowing and radiative trapping effects, should be developed to provide more comprehensive and realistic information of the urban flow and dispersion.

Models at each of the four scales proposed by Britter and Hanna [2] (i.e., regional, city, neighborhood, and street scale) have their own region of applicability and accuracy, and a detailed interpretation at one scale is commonly parameterized to assist interpretation at the next large scale. Following this proposal, nowadays some researchers turn to CFD results of street scale flows for help in formulating urban canopy models (UCM) for numerical weather prediction (NWP) models at city and regional scale. For example, based on their previous results obtained by analytical and CFD models, Solazzo et al. [69] used a drag-force approach to represent the dynamic and turbulent effects of the buildings on the flow, and a mass transfer parameterisation to take into account urban thermal effects on the flow. The resulting urban model was coupled to a mesoscale model MM5 in a simulation of Lisbon, Portugal. Ryu et al. [70] made use of their 3D CFD model results to construct the wind flow module for a new single-layer UCM.

Despite the various advantages provided by LES models, the previous LES studies suffer from problems such as small (both horizontal and vertical) computational domain, periodic boundary conditions and idealized computational settings, mainly due to the demanding computational resources required. Cheng and Liu [38] reported that their horizontal domain size ($L_x = 6h$) is not enough for the two-point correlation to vanish and thus the turbulence development is limited. Kanda et al. [71] and Michioka et al. [39] pointed out that in order to simulate properly the coherent turbulent structures developed over the street canyon, $L_x$ should be larger than $10h$. This rule should be followed in practice when dispersion and pollutant removal is of concern, as those coherent structures also contribute to the pollutant removal [39,41].

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