城市街谷的空气流动与污染物扩散研究
——物理模型的发展及数学模拟

顾兆林[1],张云伟[2]
(1. 西安交通大学 人居环境与建筑工程学院,西安 710049; 2. 西安交通大学 能源与动力工程学院,西安 710049)

摘　要:本文对关于街谷内空气流动及污染物扩散的研究进行评述。通过街谷物理模型及边界条件的分析,揭示影响街谷内空气流动与污染物扩散的物理因素,为进一步的数值预报模式的研究和数值模拟精度的提高提供思路。本文发现街谷几何结构和变化的背景风速、风向是影响街谷内空气流动与污染物扩散的主要因素。而街谷内大气稳定度和行驶车辆诱导湍流能很大程度影响街谷内的湍流强度和污染物分布,尤其在弱风环境下。在有绿化树木存在的街谷内绿化树木的影响也不容忽视。目前的经验、半经验模式对街谷模型真实性因素和气象条件考虑不够,造成模拟、预报结果误差较大。未来数值模式的发展重点在基于CFD的综合模式开发,并充分考虑街谷模型真实性因素和气象条件的影响。
关键词:城市街谷;空气流动;污染物扩散;数值模式
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A review of studies on air flow and pollutant dispersion in urban street canyons —development of physical model and mathematical simulations

GU Zhao-lin[1], ZHANG Yun-wei[2]
(1. School of Human Settlements and Civil Engineering, Xi′an Jiaotong University, Xi′an 710049, China; 2. School of Energy and Power Engineering, Xi′an Jiaotong University, Xi′an 710049, China)

Abstract: This work gives a review of studies on air flow and pollutant dispersion in urban street canyons. Affecting factors on air flow and pollutant dispersions in urban street canyons are revealed by analyzing the street canyon physical model and boundary conditions, which will provide new scopes for the studies of numerical forecasting model and for improvements of simulation accuracies. Former studies show that, the building layouts along the street and the variations of the ambient wind velocities and directions are the main factor affecting on air flow and pollutant dispersion inside urban street canyons, while the atmospheric instabilities inside the street canyons and the vehicle induced turbulence are main impact factors on turbulent characters and pollutant distributions inside the street canyons, especially under weak-wind conditions. Incase the street canyons with tree plantings, effects of tree plantings on air flow and pollutant dispersions are can not neglected. The current empirical or semi-empirical models are lacking in fully considering of the canyon real geometries and atmospheric conditions, resulting in the simulated or forecasted results with large errors. Further developing of numerical model should focus on the integration models that based on the Computational Fluid Dynamic (CFD) method, with the real geometries of the canyons and atmospheric conditions are fully considered.
Key words: urban street canyon; air flow; pollutant dispersion; numerical simulation

20世纪80年代以来,机动车尾气污染物对城市环境带来的污染问题一直受到国内外学者的关注(Colvile et al, 2001; Chan and Yao, 2008)。尤其是在超级大都市,机动车尾气污染物经常高于规定标准(WHO, 2006; Chan and Yao, 2008)。从改善城市人居环境,合理规划城市布局出发,研究城市街谷内

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通讯作者:顾兆林, E-mail: guzhaoln@mail.xjtu.edu.cn

风场特征与机动车尾气污染物的扩散规律成为重点。

早期学者通过现场实验,对街谷内空气流动与污染物分布特征有了基本了解。污染严重的情况多出现在弱来流风(背景风)或者来流风向垂直街谷的情形(Kukkonen et al,2001)。Depaul 等在上世纪 80 年代针对背景风向垂直于街谷时,城市街谷内风场和污染物分布及扩散特征进行了一系列现场观测及示踪气体(SF6)实验(Depaul et al,1983;Depaul and Sheih,1985,1986)。当背景风向垂直于街谷,街谷内流场不利于污染物扩散,街谷内污染物浓度会很高(Depaul et al,1983)。当背景风速为 1.7 ~ 4.5 $m \cdot s^{-1}$时,街谷内污染物的滞留时间为 0.7 ~ 3.8 min(Depaul and Sheih,1985)。而且,行驶车辆也会对街谷内流场的湍流特性产生明显影响(Depaul and Sheih,1986)。其他学者还对街谷内污染物浓度及垂直分布进行了观测(Hov and Larssen,1984;Puxbaum and Baumann,1984)。

后来的研究多是针对背景风向与街谷垂直时城市街谷内机动车尾气的扩散机理。Hoydysh and Dabberdt(1988)对街谷内污染物传输机理进行论述。他们认为街谷内污染物被空气环流传送到顶部,然后在亚尺度涡湍流扩散作用下穿过街谷顶部强剪切层到上部自由流动气流中。风洞实验与数值模拟方法的引入,丰富了城市街谷内空气流动与污染物扩散问题的研究手段,人们对城市街谷内污染物扩散机理有了更详细的描述。Walton and Cheng(2002)及 Li et al(2009)的数值模拟显示,当背景风向与街谷垂直时,街谷顶部污染物扩散过程主要受湍流的影响。Walton and Cheng(2002)对这一过程给出了详细描述,污染物被街谷内空气环流沿背风面传输到街谷顶部后并不能直接扩散到剪切层外,而需要积聚足够的湍动能后才能扩散到剪切层外,因此污染物在街谷顶部向外的扩散过程主要发生在迎风面附近。而 Li et al(2009)通过分析街谷顶部污染物的对流和湍流传输特性,发现湍流传输对污染物扩散起主要作用,而对流传输影响很小,但是湍流传输强度明显比其他项要低。值得一提的是,Walton and Cheng(2002)和 Li et al(2009)的数值模拟对象都是基于理想街谷假设,即街谷模型是均匀街谷,背景风速风向固定。而理想街谷模拟结果与现场测量结果往往有很大差异。因此,数值模拟和风洞实验采用的街谷模型是否反映实际街谷特征显得尤为重要。

关于街谷内空气流动及污染物扩散的研究已经有许多综述文献。Sharma and Khare(2001)从数学和数值模型、统计学模型进行了综述。Vardoulakis et al(2003)及王宝民等(2005)分别将众多研究分为现场观测、风洞实验、经验模式模拟和计算流体力学(CFD)模拟,并比较了不同方法研究结果。Ahmad et al(2005)对风洞实验模拟结果进行综述,而 Li et al(2006)则重点综述 CFD 模拟方法的发展,包括雷诺时均(RANS)和大涡模拟(LES)模拟方法。上述的文献综述均是按照研究方法的分类进行评述。事实上,各种研究方法应该相辅相成,并实现对街谷内空气流动和污染物浓度分布及扩散过程的评估与数值预报模式开发。

街谷内流场有漩涡存在,且结构复杂,但是对影响街谷内流场的街谷本身的物理模型及其影响分析不够,当前的数值预报模式仍然不能对真实街谷内空气污染状况进行很好的评估和预报(Li et al,2006)。本文通过街谷物理模型及边界条件的分析,揭示影响街谷内空气流动与污染物扩散的物理因素,为进一步研究数值预报模式和提高数值模拟精度提供思路。

1　城市街谷定义及理想街谷模型

1.1　城市街谷定义及分类

城市街谷指两侧都有连续的高大建筑物的相对狭长的街道,是组成城市冠层结构的基本单元(Nicholson,1975)。城市街谷内空气和污染物在街谷顶部与自由流动气流完成交换,因此形成特殊的微尺度气候环境(Oke,1988)。城市街谷微尺度气候环境的最主要特征是受城市边界层流动引起的街谷内流型,如街谷漩涡、峡谷效应等。

城市街谷最主要的几何特征是两侧建筑物高度和街道宽的比值,即街谷的形状因子(aspect ratio,AR)。街谷内空气流动的型态跟街谷的形状因子密切相关。Oke(1988)根据现场观测和数值模拟结果,将背景风向与街谷垂直时街谷内空气流动的型态分为三种(图 1):对宽街谷情形(AR < 0.3),街谷两侧建筑物前后形成的流场相互之间没有影响,称为孤立粗略流(isolated roughness flow,IRF);对街谷两侧建筑物之间距离减小(0.3 < AR < 0.7),街谷上风向建筑背面形成漩涡与下风向建筑前的流场漩涡相互干扰,称之为干扰流(wake interference flow,WIF);当街谷两侧建筑之间的距离近一步减小

(AR >0.7),街谷内形成独立的回流漩涡,称之为掠流(skimming flow,SF)。掠流情形下街谷内独立回流的存在限制机动车尾气污染物向外传输,因而常引起地面附近污染物浓度很高,大气环境很差,因此成为人们研究的重点(Raunemaa et al,1981;Hov and Larssen,1984;Klein and Plate 1999;Chan and Kwok 2000;Zhang et al,2011)。

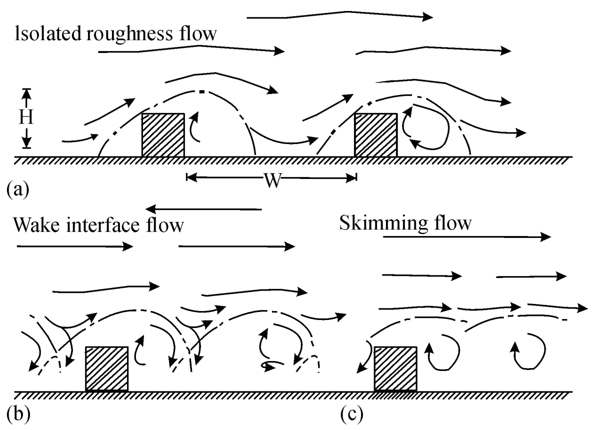

图1 不同形状因子对应街谷内的三种流型(Oke,1988)

Fig. 1 Perpendicular flow regimes in urban street canyons for three different aspect ratios (Oke, 1988)

1.2 理想街谷模型

理想街谷模型把街道两侧建筑物假设为等高的均匀分布,忽略建筑物沿街道方向的高低变化;假设建筑物壁面光滑,忽略缺口(如开窗)的影响;忽略街谷内绿化、围栏等影响因素。另外,对背景风速风向假设为稳定来流(有固定的来流风速风向)也是理想街谷模拟研究中的一个重要假设。主要研究包括数值模拟(Ca et al,1995;Walton and Cheng,2002;Cui et al,2004;Liu et al,2004;Li et al,2008a,2009)和风洞实验(Meroney et al,1996;Klein and Plate,1999;Catonet al,2003;Li et al,2008b)。研究结果表明,在形状因子接近于1的理想街谷内,空气流动由一个主旋涡主导,而在街谷顶部有一强剪切层(Walton and Cheng,2002;Cui et al,2004;Li et al,2008a)。机动车尾气污染物随街谷内空气流动主漩涡在街谷内回旋,首先在街谷底部被传输到背风面,然后沿背风面向上传输,在街谷顶部向迎风面传输的过程中部分污染物在剪切层湍流作用(Walton and Cheng,2002)下穿过剪切层到上部自由流场,部分污染物会随街谷内主漩涡沿迎风面回到街谷底部,从而形成污染物的循环流动。这种污染物的循环流动限制污染物向上部自由流场传输,因此引起街谷内污染物浓度升高,空气质量变差(Caton et al,2003)。并且,街谷背风面污染物浓度远高于迎风面污染物浓度(Meroney et al,1996;Klein and Plate,1999)。

相比之下,真实街谷环境中存在的建筑物高度变化,街谷内绿化树木,背景风速风向的变化,行驶车辆引起空气流动和湍流,街谷内温度分布不均等因素成为数值模型实际应用中的不确定因素。因此,许多工作分别针对不同的影响因素展开。

2 实际街谷特征及其对空气流动及污染物扩散的影响

2.1 街谷内温度分布与大气稳定度

太阳辐射会引起城市街谷内壁面温度分布不均,从而引起街谷内大气不稳定。受太阳直照的墙壁或地面温度明显比街谷内大气温度高(Nakamura and Oke,1988;Offerle et al,2007),而街谷大气温度几乎呈现均匀分布,大气温度的变化仅限与靠近壁面的很薄一层内(Solazzo and Britter,2007;Idczak et al,2007)。

Nakamura and Oke(1988)的实验和模拟结果都证明固体壁面温度分布不均能影响街谷内大气流动特征,甚至街谷内漩涡的方向。街谷内壁面受热方式对街谷内流动类型有着不同的影响。街谷地表受热引起街谷内大气不稳定能增加街谷内空气环流强度(Uehara et al,2000),引起街谷内空气流动主漩涡中心向迎风面偏移(Tsai et al,2005)。背风面受热使得背风面附近上升气流增强,从而增加街谷内空气环流强度(Sini et al,1995);而迎风面受热时会引起街谷内空气环流的减弱,随街谷内大气不稳定度的增加甚至会引起迎风面下角处空气流动停滞或形成单独的二次漩涡流动(Kovar-Panskus et al,2002;Xie et al,2005b)。该二次漩涡通常会限制污染物向外扩散,引起地面迎风面拐角处污染物浓度增加(Xie et al,2005b, 2007)。但是随街谷内大气不稳定度增加,该二次漩涡变大,甚至能直接与街谷上部空气进行交换(Cheng et al,2009)。

Louka et al(2000)的实验观测结果显示街谷内空气流动漩涡在不稳定大气条件下呈现很强的间歇性,气流速度的脉动值甚至比平均值要大。因此Louka等人认为街谷内空气流动漩涡的间歇性能促进街谷内通风和污染物传输,并对污染物传输产生严重影响。而Ramamurthy et al(2007)同样根据现场观测结果对大气边界层稳定性对街谷内湍流特征

的影响进行分析,结果却不明显,因为街谷内湍流强度一直很大。值得提出,Ramamurthy 等的测量点所在街谷两侧建筑物有明显高低变化,为非均匀街谷。

Kim and Baik(1999,2001)和 Xie et al(2005c)还运用 CFD 的方法研究不同壁面受热方式对深街谷和非对称街谷内空气流动的影响,发现多个漩涡的存在使得街谷内流场变化更加复杂。街道两侧绿化树木也会影响街谷内的温度分布,使得街谷内大气温度分布不再均匀(Narita et al,2008;Gu et al,2010)。

总体而言,街谷内大气的不稳定性增加了街谷内流场的湍流强度,有利于街谷顶部污染物交换(Bohnenstengel et al,2004;Xie et al,2006,2007;Huang et al,2008),尤其在微风情形下街谷内大气不稳定性的影响就更加重要(Xie et al,2006)。而逆温情况不利于污染物向外扩散(Rafailidis,2001)。

但是,Idczak et al(2007)室外模型(1∶5)实验却显示温度对街谷内流动的影响并不大,只是在近地面附近对空气流动有干扰。而 Louka et al(2002)对比观测与模拟结果发现,数值模拟的方法会高估壁面受热对街谷内空气流动的影响。因此,在数值模拟模式开发中如何正确描述街谷内大气稳定性的影响,仍然需要进一步研究。

2.2　建筑布局与结构

建筑结构对街谷内空气流动与污染物扩散的影响主要包括建筑物布局,建筑物自身几何结构以及由建筑物高度和街道宽度决定的街谷形状因子的影响。街谷两侧建筑物高度不同形成非对称街谷。而建筑物在街道的一侧在沿街谷方向上有高度变化则构成更接近于真实情况的非均匀街谷。

2.2.1　街谷非对称性

对于非对称街谷,当迎风向建筑高于下风向建筑时,称为下台阶情形流动;反之称为上台阶情形流动。风洞实验发现上台阶情形时街谷内环流强度比均匀情形时要高,有利于污染物传输(Hoydysh and Dabberdt,1988)。Venegas and Mazzeo(2000)对一段两侧建筑物高度不对称的街谷内 CO 浓度测量结果显示(测量点在低建筑一侧),当街谷内空气流动处于上台阶流情形时,CO 浓度比街谷内空气流动处于下台阶流动情形时要低。但是 Venegas 等的现场观测结果显示 CO 浓度的百分位与来流平均风速成反比,说明街谷两侧建筑物结构的影响比来流平均风速还要明显(Rafailidis,2000;Chan et al,2001,2003)。

而下台阶情形时,不同文献对街谷内流场的描述不同。可能产生上下两个反向旋转的漩涡,不利于污染物传输(Baik et al,2000;Nazridoust and Ahmadi,2006;何泽能等,2008);也有可能产生一个漩涡(Nazridoust and Ahmadi,2006)。Xie et al(2005a,2005c)数值模拟结果显示街谷内流场结构和污染物分布严重依赖建筑物布局。对下台阶情形不同模拟结果可能由街谷物理模型差异引起。

2.2.2　街谷非均匀性

而街谷一侧建筑物的高低变化对街谷内空气流动和污染物扩散的影响要更加明显。城市边界层内单个高大建筑会引起街谷内局部风速加大(Hu and Wang,2005)。而多个高层建筑的出现使得非均匀街谷内的流场更加复杂。Klein and Clark(2007)和 Nelson et al(2007)对非均匀街谷内风场观测显示,即使在顶部来流垂直于街谷轴向时,街谷内仍然有明显的沿街谷流动,甚至连经典的街谷内环流漩涡(Mazzeo et al,2007)也不明显。可见街谷非均匀性对街谷内流场结构有严重影响。

Nielson(2000)在真实街谷内发现明显垂直速度,其平均值大小与街谷顶部来流平均速度相当,并非由街谷内环流漩涡的不稳定变化引起。而 Schatzman et al(2000)则在非均匀街谷内观测到了污染物在沿街谷方向上的非均匀分布。Nelson et al(2007)根据其测量结果对非均匀街谷内流场结构给出假设,提出街谷内水平方向上流场源与汇的存在,并能引起污染物在沿街道方向形成非均匀分布。随后,Gu et al(2010,submitted)对非均匀街谷数值模拟结果验证了 Nelson 等人的假设。Gu 等对街谷的数值模拟还显示在街谷顶部有宏观尺度垂直流动存在,该宏观尺度流动由街谷非均匀性引起,并很大程度增加了街谷内污染物的向外传输。街谷非均匀性比街谷内大气稳定度对污染物扩散的影响还要明显(Ramamurthy et al,2007)。

2.2.3　建筑物几何结构

Xie et al(2005a,2005c)数值模拟结果显示街谷内流场结构和污染物分布除了受建筑物布局影响外,还严重依赖建筑物顶部几何结构。建筑物顶部几何结构对街谷内污染物扩散的影响主要是因为改变了街谷顶部的空气流动,尤其是湍流强度(Dabberdt and Hoydysh,1991)。

2.2.4　深街谷

街谷形状因子是影响街谷内空气流动类型的一

个主要因素(Oke,1988)。一般认为街谷形状因子的增加不利于污染物扩散,因此对深街谷内空气流动和污染物扩散过程的研究非常重要。然而,对形状因子大于2时的深街谷的研究至今仍有很大差异。风洞(或水槽)实验发现在形状因子等于2时街谷内出现两个反方向的漩涡(Baik et al,2000;Li et al,2008b)。Liu 和 Li 等人基于风洞物理模型雷诺数的数值模拟能够重复风洞(水槽)实验结果,并且漩涡数量随街谷形状因子增加而增加(Liu,2004;Liu et al,2005;Li et al,2008a)。而现场观测显示当街谷形状因子大于2时仍然只有一个涡存在(Eliasson et al,2006)。Zhang et al(2011)基于实际街谷模型雷诺数的数值模拟(AR = 2.7)发现街谷内只有一个主漩涡,并且其所得街谷内污染物分布与现场测量结果吻合的很好。而 Murena et al(2009)对更深的街谷(AR = 5.7)、当风向与街谷有夹角时的模拟结果显示街谷横截面上基本由一个主漩涡统治。作者推测,引起深街谷内模拟结果不同的原因可能由模型尺度引起。而模型尺度在无量纲化方程中体现为雷诺数。另外深街谷内的流场特征可能还受来流风向、建筑布局等因素影响(Murena et al,2009)。

深街谷内的流场特征,尤其是主漩涡的个数,严重影响对街谷内污染物分布的模拟结果。Li 等对 AR = 3 的深街谷内无量纲污染物浓度分布结果显示在高度方向有很大浓度梯度,街谷底部无量纲污染物浓度是顶部的约100倍(Li et al,2008a)。而 Zhang et al(2011)在对一形状因子为2.7的深街谷的模拟结果显示街谷底部无量纲污染物浓度不超过顶部的10倍,并且与实际测量结果符合的很好。从对街谷内污染物浓度预报的角度出发,适合深街谷内污染预报的新模式的开发需要保证模型满足雷诺相似。

另外,Gayev 等用风洞实验的方法研究街谷内障碍物(如小建筑,电话亭,路边停放车辆等)对空气流动和污染物扩散的影响(Gayev and Savory,1999;Gallagher et al,2011),Tokairin and Kitada(2004)用数值模拟的方法。

2.3 背景风速风向

街谷内流动在顶部风速大于 $1.2\ m \cdot s^{-1}$ 时主要受背景风驱动,而在风速小于 $1.2\ m \cdot s^{-1}$ 时则受车辆、温度等其他因素影响(Depaul and Sheih,1986;Coppalle,2001)。在顶部风速大于 $1.2\ m \cdot s^{-1}$ 的情况下,风向与街谷走向的关系影响街谷内流动类型。当风向垂直街谷时,街谷形成环流漩涡;而当风向平行街谷时,街谷内流场呈现明显的槽道流;而当风向与街谷有自由攻角时,街谷内流动是街谷内漩涡与槽道流的组合形态(Soulhac et al,2008;Yang and Shao,2008)。甚至来流风向的短时间变化都将引起街谷内流动的复杂变化(Balogun et al,2010)。

街谷内流动类型是影响污染物分布与扩散的主要因素,因此当风速大于 $1.2\ m \cdot s^{-1}$ 时,风向对街谷内污染物有明显影响(Schaefer et al,2004;Pospisil et al,2005;Rotach et al,2005;Kumar et al,2008a)。Xie et al(2009)的研究表明街谷内污染物浓度与街谷顶部风速、风向有很好的相关性。Balogun et al(2010)对街谷内外风速分布观测结果显示,街谷顶部风向的微小改变(5~10°C)都将对街谷内流场产生严重影响。

Michioka et al(2010)对二维街谷模型的模拟结果显示,街谷外流场的瞬时变化也是引起街谷内污染物向外传输的主要因素,当街谷上部流场风速变弱时将引起街谷内污染物向外喷发。Kim and Baik(2003)研究结果显示即使改变进口湍流条件也能影响街谷内污染物扩散特性。而当来流处于弱风条件时,来流风速、方向变化的影响更明显。此时对街谷内流型的经典解释都不再适用,街谷内主漩涡消失,而湍流作用很强,风速残差与平均值在一个数量级(Gadian et al,2004)。在以往研究中,来流边界条件用来流平均速度和主导风向设置,此时不再适用(Gadian et al,2004),许多经验数值模式的应用受到弱风条件的限制(Coppalle,2001)。Zhang et al(submitted)数值模拟结果显示,背景风速风向变化下街谷内环流漩涡经历大小和方向的不断变化,甚至消失。在变化的背景风速风向下,街谷内污染物的湍流扩散强度要比固定风速风向时高一个数量级。在今后数值模式的开发中,如何实现在来流风速、风向变化情况下,对街谷内空气流动和污染物浓度预报非常重要。

2.4 城市绿化

这里讨论的城市绿化主要指树木绿化。城市街谷内绿化树木的存在能阻碍污染物扩散,不利于污染物向外传输(Buccolieri et al,2011)。Gromke and Ruck(2007)和 Gromke et al(2008)对绿化树木对街谷内流场和污染物扩散的影响进行了许多风洞实验和数值模拟研究,结果显示绿化树木的存在会降低街谷环流风速,增加街谷内污染物浓度尤其是地面和背风面附近的污染物浓度,而迎风面附近污染物

浓度可能会降低(Balczo et al,2009;Gu et al,2010)。Ries et al(2001)数值模拟研究发现相同条件下,有树木绿化的街谷比裸露街谷(没有树木绿化的街谷)内污染物浓度高 8%。王翠萍等(2003)研究结果显示,道路两侧绿化树木对街谷内污染物状况的影响包括对空气的净化和对污染物扩散的阻碍,绿化树木的形式(叶面积指数)应与车流量相权衡。另外 Gu 等研究结果显示,街谷内绿化树木的存在还能改变街谷内大气温度分布,在不同太阳辐射条件下引起街谷内大气稳定度的复杂变化。这使得绿化树木对街谷内空气流动和污染物扩散影响的研究更加复杂,尤其在弱风条件下。

2.5　车辆诱导湍流

行驶车辆对街谷内大气流动及湍流都有明显影响,尤其在街谷底部。而对污染物浓度分布与扩散的影响主要来自车辆诱导湍流(Pearce and Baker,1997;Venetsanos et al,2001;Kondo and Tomizuka,2009),尤其在弱风环境下(Berkowicz et al,2002;Ketzel et al,2002;Solazzo et al,2007)。

Depaul and Sheih(1986)对街谷内风场的测量结果显示,行驶车辆的影响范围能达到 7 m 高度。而 Qin et al(1993)在现场实验中发现车辆影响能达到更高的范围(离地面 12 m 的高度)。Longley et al(2004,2004a)对真实街谷内空气流动速度和超细颗粒物(Longley et al,2004b)观测结果显示真实街谷内存在沿街谷方向的流动,车辆诱导湍流能影响 3 m 高度。实际街谷两侧建筑高度一般在 20 m(6 层楼高)以上,因此车辆行驶对街谷内流场和污染物分布的影响主要在街谷底部。Vachon et al(2002)的现场实验证明车辆诱导湍流改变街谷底部湍流特征,对背风面影响尤其明显。Ahmad et al(2002)风洞实验结果显示当街谷顶部风速较小时,车辆影响能明显减小街谷内污染物浓度。Kastner-Klein et al(2001)用风洞实验研究车流对街谷内空气流动的影响,展示了单向行驶与双向行驶车辆不同的影响效果。Mazzeo and Venegas(2005)根据现场观测结果分析车辆诱导湍流对街谷内 CO 浓度的影响,发现当顶部自由风速大于临界速度时 CO 浓度比不考虑车辆诱导湍流时低 29%。Kanda et al(2006a,2006b)和 Kondo and Tomizuka(2009)风洞实验表明行驶车辆对机动车尾气的空间扩散有明显影响,而尾气热浮力影响不大。

Di Sabatino et al(2003)和 Kastner-Klein(2003)将车辆诱导湍流参数化,并将模拟结果与风洞实验和现场观测结果比较,证明车辆诱导湍流不容忽视。Tsai et al(2005)模拟结果显示车辆诱导湍流能促进街谷底部污染物和温度的混合。Jicha et al(2000,2002)和 Katolicky and Jicha(2005)用拉格朗日方法模拟车辆诱导湍流对流场及污染物扩散的影响,得到很好的效果。

3　街谷物理模型及数值预报模式的开发

所有现场观测、风洞试验都有一个共同的目标,即为模拟、预报街谷内空气流动与污染物扩散的数值模式开发提供依据。现有的模拟、预报数值模式主要有两类。一类是根据实验数据参数化而得出的经验(半经验)模式,包括 OSPM、AEOLIUS Full、ADMS-Urban 等;另一类就是基于计算流体力学(CFD)方法的数值模式。

常用的经验模式基于实验数据提出,因此能对街谷内污染物浓度的长时间平均值,如年平均值给出很好的模拟结果;但是对街谷内污染物浓度随时间的变化模拟效果比较差。Vardoulakis et al(2007)对 24 小时平均 PM_{10}浓度的模拟结果显示有 40% 的情况模拟效果很差。在污染物浓度相对变化较大时,经验模式模拟效果更差(Raducan,2008)。另外,由于经验模式参数化受数据库内数据量的限制,经验模式的推广应用时往往伴随较大误差,需要更多实验数据校正(Manning et al,2000)。Kukkonen et al(2000)用经验模式(OSPM)模拟街谷内污染物浓度的日变化并与现场测量结果比较。结果显示经验模式所得污染物浓度日变化趋势与测量结果基本吻合,但是对 CO_2 浓度的估计偏高。而 Ghenu et al(2008)在法国应用结果显示 OSPM 低估污染物浓度,尤其是 CO。Raducan(2008) 在英国应用 OSPM 时显示模拟结果并不能很好吻合测量变化,尤其在污染物浓度变化比较大时。经验、半经验模型应用中误差较大的原因很可能是缺乏对街谷物理模型真实性因素的考虑,如街谷内均匀性、深街谷、绿化树木等。

另外,所有经验(半经验)模式在应用中还都受微风条件限制,即当背景平均风速较小时,街谷内没有明显漩涡,污染物的分布与扩散主要受温度、车流诱导湍流等因素影响时,经验模式不再适用(Coppalle,2001;Okamoto et al,2001)。因此,Solazzo et al(2007)将车辆诱导湍流模型引入 WinOSPM 模型,模拟弱风条件下街谷内 CO 浓度,使结果得到改善。

与经验模式相比,CFD 的方法对街谷内污染物分布和随时间变化的模拟结果与实验结果吻合的更好(Kumar et al,2008b, 2009; Neofytou et al,2008)。Murena et al(2009)对深街谷的模拟也显示出 CFD 方法能得到比经验模式 WinOSPM 更接近实测结果的解。由本文第3节综述可见,除深街谷外,街谷非均匀性、绿化树木、街谷内大气稳定性、车辆诱导湍流都是影响街谷内污染物浓度分布与扩散的主要因素。因此,为了达到更好的模拟、预报结果,CFD 模式需要同时考虑多种影响因素,建立综合模型。

Addison et al(2000)提出用综合模型研究街谷内污染物分布与变化规律。他们认为综合模型中要求考虑:微观的交通模型,机动车尾气排放模型,街谷内空气流动(包括对对流和湍流的描述),车辆诱导湍流(对尾气烟羽在车辆后稀释过程的影响),太阳辐射,平均风速,污染物扩散模型,建筑物布局。但是作者并没有对"微观的交通模型"具体含义给出解释。机动车尾气排放模型是源项处理的关键。而街谷内空气流动和污染物扩散模型是控制方程及其离散与求解问题。其他因素属于街谷物理模型自身因素,也是影响模拟结果的主要影响因素。

建筑物布局是一个影响街谷内空气流动与污染物扩散的主要因素,尤其是建筑物布局的非均匀性对模拟结果影响严重。而太阳辐射和车辆诱导湍流对街谷底部污染物分布与扩散有明显影响,在模拟中需要考虑,尤其在弱风条件下,二者可能成为影响街谷内空气流动(湍流)与污染物扩散的主要因素。但是本文不支持 Addison 等将平均风速看作影响街谷内空气流动的必需条件。平均风速对街谷内流动的影响远比建筑物布局要小(Venegas and Mazzeo, 2000)。反而是背景风速风向的变化对街谷内空气流动与污染物扩散的影响更加明显(Berkowicz, 1997;Balogun et al,2010;Zhang et al,submitted)。另外,街谷内绿化树木的影响也不容忽视。因此本文建议在综合模型中需要包含以下模块:

(1)描述流场的湍流模型;

(2)描述污染物扩散的多项流模型;

(3)反映街谷真实结构的非均匀街谷物理模型;

(4)绿化模型;

(5)适应真实风环境变化的背景风速、风向模型;

(6)描述街谷温度分布与大气稳定的能量模型;

(7)车辆诱导湍流模型;

(8)机动车尾气排放模型;

(9)背景浓度变化模型。

本文建议的综合模型与 Addison et al(2000)提出的综合模型有很大不同,主要体现在对背景风速、方向,绿化模型和背景浓度的考虑上。背景浓度往往是影响模式预报结果的重要因素(Ghenu et al, 2008),在有绿化树木存在的街谷内,绿化树木对污染物浓度的影响不可忽视。而非均匀街谷物理模型和真实风环境模型是改进模型的关键。另外本文对街谷物理模型的要求更加明确。

基于本文建筑综合模型中需包含的9个模块,将来的数值模式开发及数学建模需要重点处理湍流模型、边界条件、网格划分等问题。CFD 方法是求解街谷内流场的最佳选择,并且大涡模拟已经被证实其处理街谷内湍流特性的优越性(Li et al,2006)。对街谷非均匀性的考虑要更多的借助网格划分技术(罗昔联等,2009)。而对变化的背景风速风向的考虑可以借助边界条件的处理方法(Zhang et al, submitted)。背景浓度经常由中尺度预报结果给出。而关于街谷内温度、车辆诱导湍流、绿化树木、污染物排放等模块的研究已经相对成熟,只需在综合模型中引入即可。多尺度的现场观测数据是未来模式验证和改进的必要依据。

4 结论

本文通过分析当前影响街谷内空气流动与污染物扩散的各主要因素,区分了各因素的重要性及适用情形,并为将来数值模拟、预报模式的开发提供建议。

街谷几何结构,尤其是街谷非均匀性,和变化的背景风速、风向被认为是影响街谷内空气流动与污染物扩散的主要因素。而街谷内温度分布、街谷内大气稳定度和行驶车辆诱导湍流能很大程度影响街谷内,尤其是街谷底部的湍流强度和污染物分布,因此在模拟中需要考虑,尤其是在弱风环境下。在有绿化树木存在的街谷内绿化树木的影响也不容忽视。

本文对现有数值模式在对街谷内污染物浓度时空分布模拟、预报时存在的问题和缺陷进行回顾,发现经验、半经验模式对影响街谷模型真实性因素和气象条件考虑不够,造成模拟、预报结果误差较大。本文建议未来数值模式的发展重点是基于 CFD 的综合模式开发。综合模式中要充分考虑街谷模型真

实性因素和气象条件的影响。模式开发过程可以借助大涡模拟湍流模型,先进网格划分技术和新的边界条件设置方法等。而多尺度的现场观测数据对新模式的验证很有帮助。

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