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水坝泄水气体过饱和对鱼类影响及减缓技术研究综述

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摘　要: 水坝泄水总溶解气体（total dissolved gas, TDG）过饱和可导致鱼类患气泡病甚至死亡, 给水生态系统健康带来严重危害。近年来随着中国越来越多的高坝工程投入运行, 水坝泄水气体过饱和对鱼类影响逐渐成为制约高坝泄水安全运行的重要生态风险。本文通过对国内外研究文献的梳理分析, 结合研究团队近年来在该领域的研究成果, 从鱼类耐受性响应、过饱和TDG规律、减缓技术以及发展动态等几个方面对水坝泄水气体过饱和对鱼类影响及减缓技术研究开展了回顾分析。首先面向中国长江上游特有鱼类保护需求, 分析了溶解气体过饱和危害以及不同特征鱼类对溶解气体过饱和的躲避能力和耐受规律。在此基础上, 从过饱和TDG生成和释放角度, 揭示了水坝泄水溶解气体过饱和规律及其模拟预测方法, 从工程措施、调度措施和生态功能利用措施三方面阐述了过饱和气体减缓技术及其工程应用现状。基于中国高坝工程泄水生态安全需求, 开展了国内外发展动态分析, 指出进一步深入揭示高坝泄水气体过饱和机制、完善和发展高坝泄水过饱和气体预测方法和技术、加强和深化过饱和TDG减缓技术的工程可行性研究、实施基于减缓过饱和TDG影响的流域梯级多目标优化调度、推进中国关于鱼类对过饱和TDG耐受标准的建立是当前面临的关键问题与技术挑战。本文成果旨在解决水坝泄水气体过饱和问题以及高坝运行生态安全保障研究提供思路借鉴和科学依据。

关键词: 水坝泄水; 总溶解气体; 过饱和; 鱼类; 耐受能力; 减缓措施

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Review on the Effect of Dissolved Gas Supersaturation of Dam Spill on Fishes and its Mitigation Measures

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Abstract: Total dissolved gas (TDG) supersaturation caused by dam spills may lead to gas bubble disease and even fish mortality, resulting in serious negative impacts on the aquatic ecosystem. With more and more high dams put into operation in recent years, the problem of total dissolved gas supersaturation has become an important ecological risk restricting the safe operation of high dam discharge in China. By combining literature analyses and the authors' research experience in the field, the problem of dissolved gas supersaturation, its effect on fish and the mitigation measures were retrospected. First, for the protection needs of endemic fish in the upper reaches of the Yangtze River, the negative effect of TDG supersaturation and the tolerance ability of fishes to TDG supersaturation were reviewed. The mechanism of TDG supersaturation and its simulation technology was revealed from the perspective of the generation and dissipation process. The mitigation technology and its engineering application were described from the engineering measures, dispatching measures, and ecological function utilization measures. According to the ecological safety demand of high dam discharge in China, the research trend at home and abroad was analyzed. It was proposed that the current key problems and challenges mainly include further revealing the mechanism of TDG supersaturation, improving the accurate and advanced predic-

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tion methods, strengthening the engineering feasibility study of TDG mitigation technology, implementing the cascade muti-object optimal dispatching based on TDG supersaturation mitigation, and promoting the establishment of fish tolerance standards to TDG supersaturation. The effort of this paper aims at providing scientific reference and guide for the solution of TDG supersaturation and guarantee the ecological safety of high dam operation.

Key words: dam spill; total dissolved gas; supersaturation; fish; tolerance; mitigation measure

水体中溶解气体过饱和是指由于自然或人为因素引起的水体中溶解气体饱和度高于100%的现象。在这种条件下，水体中溶解气体的浓度大于当地气压条件对应的溶解气体的溶解度。水体中溶解气体包括溶解氧、溶解氮及二氧化碳等组分，各组分之和统称为总溶解气体（total dissolved gas，TDG）。在自然界中，水温突升、光合作用、水坝泄水等过程均可能导致水体中出现溶解氧、溶解氮等单一气体组分的溶解气体或总溶解气体过饱和。

当水体中过高的溶解气体压力得不到环境压力补偿情况下会析出成为气泡。大量气泡在水生生物血管或组织内聚集形成气泡或气栓阻塞血管，继而引发气肿、组织出血以及其他行为异常甚至死亡。此外，气泡在鱼体表沾附产生浮力会影响鱼的平衡和游动能力以及在水中的栖息深度，特别是对仔鱼和幼鱼的影响最为突出。溶解气体过饱和除对鱼类造成影响外，还可能对虾、蟹等水生动物造成伤害[1]。例如，蚌（*Mercenaria mercenaria*）患气泡病后鳃部充满气泡，阻止血液正常循环[2]，加利福尼亚褐虾（*Penaeus aztecus*）患气泡病后会在鳃及体表会出现气泡，导致行为异常甚至死亡[3]。

20世纪60年代由于美国Columbia河上水坝泄水运行，溶解气体过饱和引起的鱼类气泡病问题受到高度关注[1,4]。1962年McNary水坝下游大鳞大麻哈鱼（*Oncorhynchus tshawytscha*）出现因取用Columbia河中气体过饱和水源引发的气泡病问题[5]。1968年监测发现，John Day水坝下游溶解氮气饱和度达到145%。在捕获的鱼类中，25%的虹鳟（*Salmo gairdneri*）幼鱼、46%的大鳞大麻哈鱼幼鱼、68%的科霍鲑鱼（*Oncorhynchus kisutch*）幼鱼出现气泡病症状，其中在鱼类死亡数量最多的6月29日，有13条红大麻哈鱼（*Oncorhynchus nerka*）和365条大鳞大麻哈鱼幼鱼死亡。加之鱼梯过鱼效果限制，据估计当年夏天产卵的大麻哈鱼幼鱼数量减少达20 000尾[6]。

1994年8月阿根廷Yacyretá水坝开闸运行时出现因总溶解气体过饱和导致的水坝下游大量鱼类患气泡病死亡的现象[7]。Duvall等[8]报道，在1996至2002年间Priest Rapids水坝下游TDG饱和度达113%～130%期间，捕获的大麻哈鱼幼鱼中8.5%出现了气泡病症状。中国在20世纪80年代葛洲坝运行初期，曾有文献报道葛洲坝泄水的溶解气体过饱和问题[9]。李玉梁等[10]研究指出，水工泄水建筑物存在超饱和复氧状态。1994年6月，新安江水库开闸泄洪导致下游3 km的网箱虹鳟普遍患气泡病[11]。2003年8月至9月三峡大坝泄水下游黄陵庙和东岳庙断面溶解氧饱和度超过了120%，9月份最大饱和度达到130%[12]。2006年紫坪铺电站泄水下游500 m的彩虹桥断面TDG饱和度最大值为128.3%[13]。2014年7月，向家坝库区出现因溪洛渡泄水产生的气体过饱和致网箱养殖鱼类死亡事件，溶解氧饱和度的监测最高值为133%[14]，鱼类死亡数量达40余吨[15]。

针对水坝泄水溶解气体过饱和影响问题的研究主要集中在鱼类耐受性响应、过饱和TDG生成和释放规律、减缓技术等几个方面。

1 鱼类对过饱和气体的躲避和耐受能力

1.1 躲避能力

鱼类对过饱和气体的躲避能力分为水平躲避和垂向躲避能力。

1.1.1 水平躲避能力

Blahm等[16]研究发现，当水平躲避试验装置中TDG过饱和水流饱和度为130%时，虹鳟幼鱼在试验进行48 h后死亡率达50%，而大鳞大麻哈鱼幼鱼8 d后都未出现死亡，表明大鳞大麻哈鱼幼鱼具有较强的躲避TDG过饱和水体的能力。黄翔[17]和王远铭等[18]试验发现，当TDG饱和度高于125%时，岩原鲤（*Procypris rabaudi* Tchang）、齐口裂腹鱼（*Schizothorax Prenanti*）均出现明显的躲避行为，而当TDG饱和度低于115%时，鱼类在水体中自由游动，未出现躲避现象。

1.1.2 垂向躲避能力

鱼类对过饱和TDG的垂向躲避能力与水深的补偿作用相关。

水体中总溶解气体过饱和压力$\Delta P_{\rm m}$表示为总溶解气体压力$P_{\rm TDG}$与大气压$P_{\rm B}$之差：

$$\Delta P_{\rm m}=P_{\rm TDG}-P_{\rm B} \tag{1}$$

对应于当地大气压的相对饱和度$G_{\rm TDG}$为：

$$G_{\rm TDG}=\frac{P_{\rm TDG}}{P_{\rm B}}\times100=\frac{P_{\rm B}+\Delta P_{\rm m}}{P_{\rm B}}\times100 \tag{2}$$

水生生物在水深$h_{\rm B}$下实际感受到的过饱和压力$\Delta P_{\rm comp}$为总溶解气体压力$P_{\rm TDG}$与当地压力（$P_{\rm B}+\rho g h_{\rm B}$）之差。

$$\Delta P_{\mathrm{comp}}=P_{\mathrm{TDG}}-(P_{\mathrm{B}}+\rho g h_{\mathrm{B}})=\Delta P_{\mathrm{m}}-\rho g h_{\mathrm{B}} \qquad (3)$$

式中：ρ为水的密度，kg/m³；g为重力加速度，m²/s。

与此相对应，鱼类在水下感受到的过饱和度G_{comp}为：

$$G_{\mathrm{comp}}=\frac{P_{\mathrm{TDG}}}{P_{\mathrm{B}}+\rho g h_{\mathrm{B}}}=\frac{P_{\mathrm{B}}+\Delta P_{\mathrm{m}}}{P_{\mathrm{B}}+\rho g h_{\mathrm{B}}} \qquad (4)$$

水生生物实际感受到的过饱和压力ΔP_{comp}直接决定了溶解气体的生物效应。如果在水深处$\Delta P_{\mathrm{comp}}>0$，则生物体内会形成气泡甚至诱发气泡病；反之，则不会形成气泡和诱发气泡病。通常将$\Delta P_{\mathrm{comp}}=0$所对应的水深称为补偿水深。

图1为溶解气体饱和度与补偿水深的关系示意图。由图1可知，在不同深度上仪器测量的TDG饱和度（相对于大气压而言）与水生生物实际感受到的饱和度之间的关系，即深度大约为每增加1 m，饱和度降低约10%。由此表明，在具有一定深度的天然河流中，如果鱼类可以潜入一定深度下生活，则可以借助水深补偿减轻高饱和度TDG的影响。

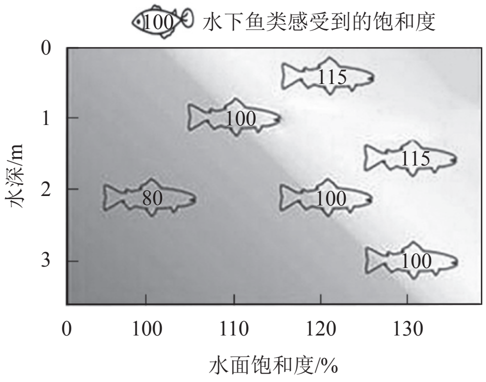

图 1　溶解气体饱和度与补偿水深的关系示意图[19]

Fig. 1　Relationship between actual total dissolved gas levels experienced by fish and various depths in the river[19]

Knittel等[20]将虹鳟幼鱼（*Salmo gairdneri*）置于TDG含量相同但深度不同的水层，结果发现深层鱼类的存活时间较长。同时，曾暴露于TDG饱和度130%的表层水体且罹患气泡病濒临死亡的虹鳟幼鱼转入水下3 m深度一段时间后，气泡病症状缓解并存活下来。Lutz[21]发现，因气泡病导致的鱼类最大死亡率并不是出现在TDG饱和度最高的时段，而是在水深最小的时段，这是因为水深较浅使鱼类无法得到足够的补偿水深以躲避TDG过饱和影响。Backman等[22]观测发现，由于缺少补偿水深作用，室内试验的鱼类气泡病发病率显著较天然河流高，过鱼通道中鱼类气泡病症状较坝上和坝下深水区更为显著。Harmon[23]和Beeman[24]等研究发现，鱼类可以利用补偿水深来减弱或避免TDG过饱和伤害，在补偿水深以上生活的鱼类更易受过饱和TDG伤害。谭德彩[25]研究发现，三峡泄水期间，生活在水体底层的鱼类对TDG过饱和有较强的耐受性。黄翔[17]室内试验发现，在TDG饱和度为150%条件下，水深30、130、230 cm处岩原鲤半数死亡时间分别为0.9、2.8、8.6 h，说明水深增加产生的补偿水深作用减弱了过饱和TDG对鱼类的伤害。这也从另一方面解释了为什么TDG过饱和的天然河流中野生鱼类死亡率较低，而网箱养殖鱼类死亡率较高的现象。

1.2　不同组分气体的致病作用

虽然溶解氧、溶解氮和总溶解气体的饱和度超过一定值时均可能使鱼类患气泡病甚至死亡，但由于氧气在生物机体内除了以溶解态存在外，还可与血红蛋白结合，通过生物过程得到消耗或降解，而氮气是惰性气体，在生物体内不能参加新陈代谢，由此导致溶解氧的致病作用小于溶解氮和总溶解气体。

早期的试验研究发现，在只有溶解氧过饱和情况下，溶解氧饱和度通常达到300%以上才可能致使鱼类患气泡病[3]，大菱鲆[26]（*Scophthalmus Maximus L.*）、虹鳟鱼[27]、大西洋鲑（*Salmo salar*）[28]等均对过饱和溶解氧的耐受能力较强。Rucker[29]研究发现，在总溶解气体饱和度恒定为119%的情况下，溶解氧和溶解氮的比例在159∶109以下变化时，不会对鱼类产生显著影响，但在氧氮比例上升为173∶105时，气泡病发病率出现急剧下降。

Doudoroff[30]试验证实，气泡病主要是总溶解气体而不是单一溶解氧或溶解氧造成的。Rucker等[31]将大鳞大麻哈鱼的鱼苗分别持续暴露在氮气饱和度120%，但TDG饱和度不同的水体中，在TDG饱和度为116%的环境中35 d仍未出现大量死亡现象，但在TDG饱和度为120%的环境中，幼鱼在25 d即出现大量死亡。Meekin等[32]试验发现，大鳞大麻哈鱼幼鱼在10 cm深的井水容器中（氮气饱和度122%，TDG饱和度112%）5～10 d内死亡率2%～5%，而在61 cm深的河水容器（氮气饱和度124%，TDG饱和度123%）5～7 d内死亡率达92%～100%，说明TDG的致病作用大于溶解氮气。对天然水体中TDG和DO相关关系分析表明，水体中DO浓度随着水体污染程度的改变而发生变化，因此DO变化幅度通常较大，而TDG变化相对较小。特别是天然河流中，TDG和DO的相关关系具有不确定性，因此在气体过饱和对鱼类影响研究中，部分研究针对溶解氧，而更多研究采用总溶解气体[33]。

1.3　鱼类对过饱和TDG的耐受规律

1.3.1　鱼类耐受性与过饱和TDG暴露条件的关系

1）持续暴露条件下的鱼类耐受性

鱼类耐受性成果较多来源于室内试验。大鳞大

麻哈鱼幼鱼在TDG饱和度110%、水深28 cm的浅水中暴露28 h未出现死亡，且几乎未发现气泡病症状；在TDG饱和度120%水体中暴露58 h死亡率43%[34]；在TDG饱和度130%水体中暴露5 h开始出现死亡，9 h死亡率为50%[35]。岩原鲤鱼苗在TDG饱和度低于115%的室内水体中均能存活，在TDG饱和度120%以上时陆续出现死亡[36]。白鲈（*Atractoscion nobilis*）持续暴露于TDG饱和度低于110%的水中，96 h未出现死亡，但在TDG饱和度为122%的水中，鱼体内出现气栓并发生死亡。在TDG饱和度130%以下的水体中，鲟鱼（*Acipenser dabryanus*）耐受性随悬浮物含量增加而降低，在更高饱和度水体中，悬浮物含量对鱼的耐受性影响不明显[37]。

由于室内试验与具有水深补偿作用的天然水体存在较大差异，因此对野生鱼类影响的跟踪调查以及原位试验研究至关重要。Columbia流域多个水坝下游现场监测表明，TDG饱和度低于120%时，野生鱼类致病率普遍小于10%，显著低于室内试验结果[38]。Columbia河Rocky Reach和Rock Island河段1997年连续两个月TDG饱和度超过120%，捕获的鲑鱼幼鱼20%～80%出现气泡病症状[39]。Snake河Hells Canyon河段连续30 d TDG饱和度超过120%，63%的渔获物患气泡病[40]。金沙江向家坝电站和大渡河大岗山电站下游开展的原位试验表明，TDG饱和度在120%以上时试验鱼出现死亡，超过125%时死亡较严重[41]。借助深度传感器和声学发射器对挪威Otra River 94条褐鳟鱼（*S. trutta*）生活水深的跟踪监测结果表明，在TDG饱和度为133%以下的天然水体中，除9条鱼由于过弱的水深补偿功能而致死外，其余鱼类均利用补偿水深作用有效避免了TDG过饱和的影响[42]。由此可以总结认为，连续长时间的高饱和度暴露导致气泡病患病率增加，天然河流120%饱和度条件下，鱼类气泡病症状不明显。

2）TDG过饱和间歇性暴露对鱼类恢复的作用

在天然水体中，TDG饱和度可能随时间呈现非恒定变化过程。此外，鱼类上下游动使其处在过饱和TDG间歇性暴露中[43]。Monk等[44]将虹鳟鱼标记后放置于Snake河下游水深46 cm、TDG饱和度为113%～117%的水中暂养，然后将出现严重气泡病的鱼类重新放回到河流中，结果发现53%的鱼苗气泡病消失。Gale等[45]将数条大鳞大麻哈鱼成鱼暴露在0.5 m深、饱和度为114%～126%的水中直至出现鱼死亡或接近死亡，而后将试验鱼重新放回到天然环境中，之后未观测到过饱和TDG预暴露对鱼类产卵的影响。这一试验表明，间歇暴露有助于患气泡病鱼类的恢复。冀前锋等[46]试验研究了通过间歇性暴露延长鱼类在过饱和水体中生存时间的可行性。

1.3.2 不同鱼类对过饱和TDG的耐受性差异

Fickeisen等[47]试验证实，TDG饱和度120%以上所有的白鲑（*Prosopium williamsoni*）和褐色鲑（*Salmo clarki*）2～4 d内全部死亡，而大鳞亚口鱼（*Catostomus macrocheilus*）存活10 d以上的比例为20%，急流杜父鱼（*Cottus rhotheus*）存活10 d以上的比例达70%。Abernethy等[48]试验发现，蓝鳃鱼（*Lepomis macrochirus*）对过饱和TDG的耐受能力大于大鳞大麻哈鱼和虹鳟鱼。Beeman等[49]试验表明，Columbia流域大鳞亚口鱼等5种土著鱼苗在TDG过饱和水体中的半致死时间存在显著差别。黄翔[17]、Wang等[50]试验发现，暴露在TDG饱和度115%以下水体中的岩原鲤、齐口裂腹鱼、胭脂鱼等鱼类均未出现死亡，在120%和125%时，耐受性由弱到强的顺序大致为齐口裂腹鱼、岩原鲤、胭脂鱼（*Myxocyprinus asiaticus* Bleeker），130%及以上环境，耐受性由弱到强的顺序大致为岩原鲤、胭脂鱼、齐口裂腹鱼。可见不同鱼类对过饱和TDG的耐受性差异较大。

1.3.3 鱼类不同生长阶段对过饱和TDG的耐受性差异

Nebeker等[51]认为，卵壳的保护可以使鱼卵和前期幼鱼更能抵御TDG过饱和影响。Bouck[52]研究得到，鲑鳟鱼幼鱼死亡率20%时对应的死亡时间为125 h，而两龄鱼为154 h，成鱼为309 h。Wood[53]根据不同阶段大麻哈鱼的耐受性结果，提出了相应耐受性阈值建议：仔鱼为103%～104%、幼鱼为105%～112%、成鱼为118%。Krise等[54]研究发现，刚孵化出的仔鱼对TDG过饱和有较高的耐受性，到幼鱼阶段耐受性降低，随着幼鱼生长，耐受性又会逐渐增强。Bohl[55]指出，大麻哈鱼幼鱼的鳃结构、骨骼发育、血管及神经系统在TDG饱和度为102%的水体中均遭到了严重损害，而成鱼的起始TDG致死浓度为116%。总结认为，鱼卵和幼鱼前期的耐受性强于幼鱼后期，而幼鱼耐受性普遍较成鱼弱。

1.4 鱼类对过饱和TDG的耐受性标准

美国国家环保局于1986年将110%设定为TDG过饱和的标准[56]。加拿大规定水深大于1 m时，溶解气体分压小于76 mmHg（约110%），而在水深小于1 m及鱼类孵化场等环境中，溶解气体饱和度限值根据实际情况实行更为严格的控制[57]。上述标准的制定较早，且主要依据室内试验结果。近年来美国Washington和Oregon州建议将TDG饱和度限值提高至120%。Schneider[58]认为，在具备补偿水深的河流，120%～125%的TDG饱和度不会引起洄游鲑鱼的死亡。中国目前尚无相关标准。

2　水坝泄水气体过饱和规律

2.1　气体过饱和生成过程

对过饱和溶解气体生成过程的研究大体经历了经验或半经验公式、物理解析模型、单相流模型再到两相流模型几个阶段。

经验或半经验公式多根据特定水坝泄水建立，简单易用。Pickett[59]、Witt[60]等根据Columbia流域监测结果，建立了考虑泄水与发电流量、水深等影响的过饱和TDG预测经验公式。王煜等[61]采用主成分分析方法得到高坝泄水溶解氧过饱和主要影响因子包括流量、水头、坝前饱和度等因子。Kamal[62]和Lu[63]等分别根据不同水坝的气体过饱和原型监测成果，分析建立了过饱和TDG生成与泄流流量、水头、水垫塘消能效率的关系。

物理解析模型将气液传质与泄水物理过程相结合进行研究。Roesner等[64]最初分析了泄水过饱和气体传质过程，Johnson[65]在此基础上提出了坝面溢流过饱和气体传质模型。Hibbs等[66]通过追踪甲烷以及氧气饱和度的变化，推导得到泄水过程中气体传质效率。Geldert等[67]采用2/3水深为气泡有效深度，考虑自由界面与气泡界面的传质，建立了底流过饱和TDG传质公式。Li等[68]将挑流泄水过饱和TDG传质概化为消力池内气体过溶与二道坝下游突然释放过程，分析建立了挑流泄水过饱和TDG传质模型。Lu等[69]进一步考虑挑流水舌的空中掺气与传质过程以及消力池内滞留时间影响，完善了挑流泄水过饱和TDG传质模型。Li等[70]分析建立了考虑气泡尺寸及环境水体中溶解气体浓度影响的气泡上升过程中气泡–水界面溶解气体传质系数模型。

单相流模型和两相流模型建立在水动力学方程基础上，较经验公式和物理解析模型在精度、通用性等方面都有很大改善。Orlins等[71]基于物理模型试验得到的流场分布，采用宽度平均立面2维紊流数学模型模拟过饱和TDG时空分布。Weber等[72]基于单一气泡粒径假定，建立了同时模拟流场和TDG的单相流过饱和TDG模型。Urban等[73]考虑气泡聚并对过饱和TDG生成的影响，建立了2维紊流数学模型，其中考虑气含率在主流区、回流卷吸区和下游尾水区的不同。Politano等[74]引入气泡数量密度方程模拟各组气泡数量时空分布变化，考虑TDG传质和气泡压力变化对气泡大小的影响，首次将两相流模型用于TDG模拟研究中。覃春丽[75]和Fu[76]等分别建立了葛洲坝过饱和TDG两相流传质模型。Yang等[77]提出了基于VOF与气泡正态分布假定的TDG模型。Wang等[78]借助OpenFOAM开源平台，结合VOF方法和漩涡模拟，进一步发展完善了两相流模型。Huang等[79]引入Castro紊动掺气模型[80]，提出了基于紊动漩涡掺气的过饱和TDG紊流模型并应用于中高坝模拟中，大大改善了对强紊动射流掺气及其传质影响的模拟精度。

2.2　气体过饱和释放过程

水坝泄水产生的过饱和TDG在随水流向下游输移过程中，主要通过自由界面传质缓慢释放。国内外关于自由界面传质规律的研究成果较丰富[81–83]，其中有关于二氧化碳和温室气体传质系数的研究[84]，还有关于溶解氧传质的研究，但多针对非饱和态向饱和平衡态转变过程，而关于TDG由过饱和态向饱和态转变过程的研究却较少。

华盛顿大学认为过饱和TDG在水坝下游河道的释放服从于一级动力学过程[85]。Johnson等[86]采用MASS2模型了Bonneville Dam和Ice Harbor Dam下游河段过饱和TDG的空间分布。Politano等[87]借鉴溶解氧传质系数研究成果，采用3维两相流模型模拟了Wanapum坝下游1 000 m范围内过饱和TDG的演变过程。中国水利水电科学研究院、清华大学等单位基于对三峡电站下游河段DO监测，采用1维模型模拟预测了溶解氧沿程变化，其中假定过饱和DO释放系数等于河流复氧系数[88–90]。Johnson等[91]采用深度平均2维数学模型模拟得到了Bonneville与Ice Harbor坝下数千米长的河道内TDG分布，其中过饱和TDG释放系数考虑了风速影响。冯镜洁等[92]基于原型观测和机理试验，提出考虑紊动影响的释放系数估算方法。Feng等[93]将过饱和TDG释放过程概化为水体内部TDG释放和自由表面的传质释放，建立了大型深水库宽度平均立面2维过饱和TDG输移释放模型。李纪龙[94]采用平面2维过饱和TDG释放模型对向家坝下游河段过饱和TDG释放过程开展模拟研究。Kamal等[95]根据Columbia流域过饱和TDG监测成果，分析了过饱和TDG横向和纵向分布规律及沿程释放系数。冯镜洁[96]、Ou[97–98]、Yuan[99]等试验研究表明，升温、曝气以及泥沙、植被等阻水介质对过饱和TDG的释放具有明显促进作用。

综合分析表明，已有关于过饱和TDG释放过程的研究常采用由不饱和态向饱和平衡态转变过程的研究成果，其中一些研究直接将氧亏水体的复氧系数作为TDG过饱和水体的释放系数。如此处理对以气泡界面传质为主的近坝区过饱和TDG的生成影响较小，但对以自由界面传质为主的下游水体释放过程的预测则会带来较大误差[100]。

3　水坝泄水气体过饱和影响减缓技术

对气体过饱和水体处理措施的研究最早源于对

低流量养殖水源的处理，主要有虹吸法[44]、填料柱法等[101–103]。水坝泄水气体过饱和减缓技术主要分为工程措施、调度措施以及局部重点区域生态功能利用措施。

3.1 工程措施

典型的工程措施包括在溢洪道导流坎、阶梯溢洪道、挡板溢洪道、辅助消能墩等。

导流坎作用主要是将掺气水流导向消力池表层，从而避免进入底层高承压环境导致过高饱和度[104–105]。导流坎适用于底流消能的低水头水电站，最早在1972年被应用在Columbia河Bonneville水坝，使TDG饱和度降低3%～12%[59]。

阶梯溢洪道或挡板溢洪道是在溢洪道内布置阶梯或挡板，一方面促进水流消能，避免水流潜入消力池底部从而减小TDG饱和度增加；另一方面促进坝面水流的水气界面传质，从而改善溶解气体水平[78,106]。

辅助消能墩布置在消力池内或水垫塘二道坝下游，主要通过提高消能效率、促进气泡向水面的运动及过饱和气体向水面的释放。Huang等[79]对大岗山电站和铜街子电站泄水的模拟研究表明，底流与挑流泄水下游增设消能墩可以有效降低过饱和TDG的生成。

由于各项工程措施技术难度大，并且与工程安全密切相关，因此即使在筑坝技术高速发展的今天，过饱和TDG减缓措施的工程应用仍是一关键难点问题。

3.2 调度措施

国内外关于泄水调度减缓过饱和TDG影响的研究一直在持续开展中[77]。Frizell[107]基于Columbia河Grand Coulee大坝TDG饱和度控制目标，研究了溢洪道和发电的上限流量。Pickett等[59] 研究了Columbia河梯级电站流量协同调度问题。Politano等[108]模拟研究了通过分散泄洪等方式减小TDG影响。彭期冬等[109]提出动态汛限调度方式减缓三峡电站溶解气体过饱和影响。Feng[93,110]开展了利用水库调度减缓过饱和TDG影响的模拟研究，表明优选泄水建筑物结合梯级联合调度有助于减少高流量泄水持续时间，从而在一定程度上降低梯级过饱和TDG水平。Ma等[111]模拟研究表明，与持续泄水相比，间歇泄水有助于减轻TDG过饱和对鱼类的影响。Wan等[112]基于鱼类耐受性成果，建立了动态多目标TDG管理模型，从降低TDG过饱和水平和最小化TDG停留时间角度提出了水库脉冲泄水方式。近年来，优选泄水建筑物、分散泄水等技术在金沙江下游等流域梯级泄水调度中得到应用，有效减缓了泄水生态影响。

3.3 生态功能利用措施

利用鱼类对气体过饱和的躲避能力，充分发挥干支流交汇区、河滩区、水体深层等区域生态功能，减小气体过饱和影响。Shen等[113]研究表明，利用支流饱和度较低的特点，同时辅以顺坝、阻流桩等工程措施，可以在干支流交汇区营造一定的TDG低饱和度区。Ou[98]、Yuan[99]等研究表明，对局部重点区域实施曝气、布置阻水介质等措施，有利于降低TDG饱和度，为鱼类躲避过饱和TDG影响创造有利条件。

4 发展动态分析

根据对国内外研究现状的梳理分析，基于中国高坝泄水生态安全需求，高坝工程溶解气体过饱和领域亟待解决和深入研究的问题主要有以下几个方面：

1）由于高坝泄水掺气以及过饱和溶解气体生成过程在原型和模型之间难以建立相似性规律，而现有监测技术难以实现挑流泄水近区的过饱和气体原型监测，因此有待综合更为先进的测试与试验手段，从微观角度深入揭示高坝泄水气体过饱和传质机制。

2）高坝泄水空间尺度大，计算区域复杂，气液界面传质模拟存在收敛性和经济性等限制，同时模型参数率定的可靠性有待提高。在深化传质机制认识基础上，借助先进的数值模拟技术进一步完善和发展高坝泄水过饱和气体预测研究势在必行。

3）溶解气体过饱和减缓技术的研究方兴未艾。从降低过饱和气体生成、加快过饱和气体释放以及重点区域生态功能利用等方面，加强和深化过饱和TDG减缓技术的工程可行性研究，推动减缓技术在实证工程的应用是实现高坝泄水生态安全的关键问题。

4）流域水电梯级开发格局基本形成。为此，关注连续梯级开发的过饱和TDG累积影响，探求基于减缓过饱和TDG影响的流域梯级多目标优化调度，是未来溶解气体过饱和问题研究的重要方向。

5）针对不同流域目标鱼类和典型鱼类的保护需求，在深化鱼类耐受性研究基础上，提出鱼类对过饱和TDG的耐受阈值，为中国水环境标准中TDG限值标准的制定以及水坝泄水生态安全提供理论指导和科学依据。

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