Plumbing Engineering Services Design Guide

The Institute of Plumbing

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h. Provide duplicate interface valves in gutters to provide backup in the event of one becoming stuck.

i. Hold adequate supplies of spares on site to assist in the routine maintenance of the plant.

Vacuum drainage systems

Introduction

Vacuum systems for the transportation of waste water can be divided into two basic systems; within buildings and outside buildings. European Standards, adopted as British Standards, have been written for these two systems. The Standards contain the design, installation and performance requirements for vacuum drainage and vacuum sewerage systems. However, such systems are currently manufactured by a few international companies that fiercely safeguard their system design details. Hence, although the Standards specify the requirements for systems and set out the design principles, the actual design process depends upon the performance of the individual components and the design philosophy of the manufacturer. The main manufacturers of vacuum systems use different design philosophies and this results in their use of different pipe sizes, pipework configurations and interface valve sizes. It would be wrong for this book to recommend one manufacturer's system, as each prospective installation usually requires a unique design. Unlike a conventional gravity drainage or sewerage system, a vacuum system should be considered as a complete machine and not a simple hydraulic network. Engineers often want to be able to design a vacuum system in the same way that they would design conventional systems. However, currently the information they require, such as the performance characteristics of the interface valves, is not in the public domain. Hence, designers, specifiers and clients are only able to use the Standards, and information such as this section, to help them decide if a vacuum system is applicable for the project they have in mind, and agree an informed specification for any system.

Background

Generally, the modern vacuum drainage system is believed to have been started by the development of the vacuum toilet by Mr Joel Liljendhal in the mid 1950s. The concept of his system was to separate the heavily polluted waste and the lightly polluted water (black and grey water) for separate treatment. The vacuum toilets used only about 1 litre of water per flush improving the efficiency of the system and making treatment easier. This two-pipe system, although environmentally friendly, met with quite a lot of resistance because houses needed to be re-plumbed and the vacuum toilet required more maintenance than a conventional toilet. This led to the development of the single pipe vacuum drainage system generally employed today.

Whilst the original systems were developed for domestic wastewater transportation, the systems evolved in two different areas; transportation and land-based systems. The majority of work has been in the transportation sector, and the marine industry continues to be the major user of the system, where the need to conserve wholesome water, and the problems of confined pipework runs and sewage disposal are paramount. For the same reasons this technology was adopted by the other forms of mass transport, ie airlines and railways. Today some 5,000 ships, from yachts to cargo vessels to ocean-going cruise liners, 50 major airline companies, and over 100 train installations use vacuum drainage systems.

The buiding sector has been slow to adopt this new technology, but with the restrictions placed on new projects such as small conduit, ceiling voids and service ducts, and the growing awareness of the need to limit water consumption, the system is finding a place in the building sector.

Applications

Particular consideration should be given to the use of vacuum drainage in the following circumstances:

a. Water shortage or other reasons for reducing water consumption

b. Limited sewerage capacity

c. Where separation of black and grey water is desired, eg where grey water is reused

d. Where separation of wastewaters is desired, eg for different treatments

e. In hospitals, hotels, office buildings or other areas where congested usage occurs

f. When flexibility in pipe routing is required to drain appliances or where frequent pipe layout changes are expected

g. Building refurbishment

h. Where drainage by gravity becomes impractical

i. In complex building structures and

j. In penal installations where isolation and control of the appliances is necessary to prevent concealment of weapons and drugs.

Black and grey water

The collection arrangements and small bore pipework of vacuum drainage systems provide the possibility of easily separating grey and black water. This was one of the original aims of the invention by Mr Liljendhal. This would be of particular advantage if sewerage capacity was at a premium as the grey water could be run to a water course after preliminary treatment. Also, it would be of advantage if there was a requirement to use the grey water for reuse or irrigation.

Retrofit and newbuild flexibility

When conventional gravity drainage systems are extended as in refurbishment work, the existing gravity drainage system can be fed into the vacuum drainage system. This may be achieved by the use of a sump into which the wastewater from the gravity system drains. When sufficient water has accumulated in the sump, an interface valve will open allowing the wastewater to enter the vacuum drainage system. This arrangement can also be used to collect rainwater or as an interface between a building with conventional drainage and a vacuum sewer.

System descriptions

Definitions of terminology

A selection of the fundamental definitions that are required to understand the terminology of vacuum drainage systems are listed below. A complete set of definitions is contained within the European Standard EN 12109.

Buffer volume: The storage volume of the interface unit which balances the incoming flow of wastewater to the output capacity of the discharge valve.

Controller: The device which, when activated by its level sensor, opens the interface valve and, after the passage of wastewater and normally air, closes the valve.

Interface valve: A valve which admits the flow of wastewater only or wastewater and air into the vacuum drainage system pipeline.

Lift: Section of vacuum pipeline with an increase in invert level in the direction of flow.

Reforming Pocket: A low point in the piping profile installed intentionally to produce a controlled slug flow.

Service Connection: The section of vacuum pipeline connecting an individual interface unit to the vacuum main.

Slug: An isolated quantity of wastewater flowing full bore through the vacuum pipeline.

Vacuum: Any pressure below atmospheric.

Vacuum Station: An installation comprising vacuum generator(s), a means of discharge, and control equipment and which may also incorporate vacuum vessel/holding tank(s).

The vacuum transport process

An understanding of the vacuum transport process is helpful to the system designer. As long as no interface unit is operating, little wastewater transport takes place. All wastewater remaining in the vacuum pipework will drain, by gravity, into the reforming pockets when all upstream interface valves are closed. When an interface valve opens, the differential pressure between the vacuum in the system and atmosphere, forces the wastewater into the vacuum pipework. Whilst accelerating, the wastewater is transformed into foam and soon occupies only part of the vacuum pipe cross section so that the momentum transfer from air to water takes place largely through the action of shear stresses. The magnitude of the propulsive forces starts to decline noticeably when the interface valve closes but remain important as the admitted air continues to expand. Eventually, friction and gravity bring to rest the wastewater at the low points of the pipework system; such as reforming pockets and at the bottom of pipeline lifts.

The vacuum drainage system transports wastewater by means of atmospheric pressure acting against vacuum.

When designing systems greater than 100m in length (from the valve to the vacuum station), a series of reforming pockets must be used. These minimise the break-up of the wastewater slug and reform that portion of the slug that remains in the piping between interface valve discharges. The reformed slug is then propelled by the air admitted during the next discharge.

Once the interface valves have operated, the discharge travels to the vacuum station, normally located at ground or basement level. Air is discharged to atmosphere only from the vacuum station. From the vacuum station, the wastewater is pumped automatically to the building outfall connection, to discharge into the external drainage system by gravity.

To design a reliable and economic vacuum drainage system, it is necessary to generate sequentially high acceleration and self-cleansing velocities with the least amount of energy.

NOTE:
A vacuum drainage system is NOT a reversed pressure system where all the water would be accelerated simultaneously.

Basic components

A vacuum drainage system may be considered as comprising four elements:

a. The automatic interface units (AIU)
b. The vacuum toilets
c. The pipework
d. The vacuum station.

Interface units

The valves that form the interface between the vacuum drainage lines and the appliances can be used directly with some appliances and with buffer volumes for others. When used with buffer volumes, level sensors and controllers, the valves are termed interface units (AIUs). Although AIUs are operated by air, non-automatic units may use electricity to control their operation.

They are of various sizes of interface valve up to about 100mm bore. The larger valves are used in vacuum sewerage systems.

Typically a complete interface unit is composed of a buffer volume of varying size, a sensor to sense the wastewater level in the buffer volume, a controller which operates a pilot valve to open and close a vacuum supply line to the interface valve. In many designs of interface unit, level sensors and controllers are combined into one device.

Vacuum toilets

A vacuum toilet uses air instead of water to remove the contents of the bowl, and is a form of interface valve. Usually, it includes a flushing rim and the toilet's controller may have a memory function so that it will operate as soon as there is sufficient vacuum available.

Typically, when operating a flush button, pressurised water is introduced into the bowl through a water valve and a flushing ring with holes to clean the bowl. Simultaneously the interface valve opens and the pressure differential in the piping forces the contents through the valve. Before the interface valve closes, air is drawn into the pipe. The flush water valve stays open for about two seconds to re-establish the water pool in the bowl. The typical water consumption for this timing sequence would be 0.8-1.5 litre per flush. Vacuum toilets may be re-flushed in less than a quarter of the time taken for a conventional WC to refill, on average, a vacuum toilet will take 3 seconds to complete a flush cycle.

Ejector unit

Ejector units are used on small systems, which require approximately 40m^3 of air an hour at peak flow. They have the advantage of having a lower capital cost, being small in physical size and with fewer working parts than vacuum pumps, and are easy to maintain and operate. However, they are less power efficient than a conventional vacuum station and, therefore, are more expensive to run. The control of this kind of vacuum station is similar to a conventional pumping station. These units can also receive discharges from gravity drainage systems directly into the tank. However, wastewater containing high levels of detergents may cause foaming problems.

Vacuum station

A vacuum station has three functions:

i. Generate vacuum
ii. Receive and forward the wastewater and
iii. Control and monitor the system.

Although vacuum stations may be used with similar systems as the ejector unit, they are used mainly for larger systems, ie greater than 40m^3 of air. They are large units with a higher capital cost but typically are cheaper to run than ejectors.

The machinery installed is similar to that of a conventional wastewater pumping station or lift station, and consists of a collection tank, wastewater forwarding pumps, vacuum pumps, controls and alarms, and where required a standby generator.

The vacuum receiver tank size and/or number of tanks depends on the number of appliances connected to the system and the expected frequency of discharge. Each tank incorporates level switches that control the discharge pumps automatically, vacuum regulator switches which control the vacuum pumps and level alarms which can be audible or connected to the building management system.

Vacuum generating and forwarding pumps

Vacuum generating pumps

Vacuum pumps of the liquid ring and sliding vane types are both suitable for use in vacuum drainage systems. Vane type vacuum pumps are recommended for most projects since they are more efficient, ie they have a greater throughput of air and are less temperature sensitive than similarly powerful liquid ring pumps.

The maximum vacuum provided by a liquid ring pump often will not exceed –0.8 bar gauge, whilst the maximum vacuum of a vane pump will typically be closer to –1 bar gauge. This will affect the choice of pumps where vacuum levels of a greater magnitude than the normal –0.5 to –0.7 bar gauge operating range will be required, or for projects at high elevations where atmospheric pressure is lower.

A vacuum switch attached to the pipework and adjustable timer are used to control the vacuum pumps. A second vacuum switch may control a low vacuum control alarm signal. These switches are fitted with stainless steel bellows to protect against corrosion from any gases evolving from the wastewater.

Forwarding pumps

Forwarding pumps are required to discharge the collected wastewater to the external gravity sewerage system. These pumps are designed to operate with a large pressure differential across them with their inlets under vacuum. The size of the forwarding pump is a function of the following: design peak flow, volume to be discharged, and the permissible discharge rate for the receiving sewer.

To enable some forwarding pumps to work, a vacuum balance line may be required down stream of the discharge pump to reduce the pressure differences across the pump (a balance line is not required with an ejector system). To prevent loss of vacuum when the pump is not discharging, a check valve is required in the discharge pipework downstream of the connection of the balance line.

Controls

System controls

The vacuum drainage system control panel contains the main power switch and the pump operating system which includes: magnetic starters, overload protection, control circuitry and hours run meters for each vacuum and forwarding pump. A data recorder may be built into this panel, as well as the collection tank level control relays. Alarm and telemetry systems may also be included if required.

Pump controls

The controls should be designed so that, where stand-by pumps and collection tanks are installed, both the vacuum and forwarding pumps alternate their use and are interconnected and controlled to allow them to be used with either tank automatically. The pump controls will include logic controllers that will be connected to the various level and vacuum sensors. The signal to start the discharge comes from the high level switch in the collection tank, the stop function is either controlled by a low level switch or timer. For example, when the high level sensor indicates to the logic control that water has risen to the high level, this sequence of operation will commence:

i. The controller will close automatic valve in balance line, where fitted, and start the forwarding pump
ii. If level does not fall within the pre-set time, a second pump will be started or an alarm generated
iii. If level reaches the high level alarm sensor, then an alarm is given and the vacuum system is shut down
iv. When the water level has fallen to a low level sensor or after a pre-set time period, the controller will stop the forwarding pump(s) and open the automatic balance line valve, if fitted.

In systems where only black water is being collected it is prudent to use the second forwarding pump as a circulation pump. This circulates sewage within the collection tank and breaks up any solids which may have formed on the surface of the wastewater. This operation should be programmed into the logic system as the first step in the discharge cycle.

Collection tank level controls

Level detectors are available in various forms, some are float switches, others are fixed probes that may be conductive, inductive or capacitative. Where a lot of condensate is being collected, for example in supermarkets with chiller cabinets, the mineral content of the water may affect the operation of the system and conduction probes may need to be used.

Level detectors, of some form, are fitted to all collection tanks. The signals from the six common detectors control the discharge pumps and alarms as follows, in accending order of height from the base of the tank:

i. Earthing probe, or sensor float switch or similar
ii. Both forwarding pumps stop
iii. Lead forwarding pump start
iv. Assist forwarding pump start
v. High level alarm
vi. High level cut-off – stop vacuum pumps.

Vacuum gauges

It is important that all vacuum gauges be specified to indicate gauge pressure and have stainless steel bourdon tube and socket.

Vacuum gauges should be provided at the following locations in positions that can be viewed easily:

a. the side of the vacuum moisture removal tank (where fitted)
b. the collection tank
c. one gauge on each incoming vacuum main or header.

It is important that these gauges are located above the incoming pipes and in a position that is easily viewed from the operating position of the isolation valves.

Combined vacuum generator and forwarding pump

A combined vacuum generator and forwarding pump or 'vacuumarator' is a screw vacuum pump with liquid ring seal with a macerator for breaking up any solids passing through it. The macerator consists of one rotating knife fixed to the shaft and one stationary knife fixed to the suction chamber.

The combined vacuum generator and forwarding pump;

a. generates vacuum
b. macerates solids
c. pumps wastewater in the same operation.

A combined vacuum generator and forwarding pump can generate vacuum directly on the pipeline to an appliance and discharge to a gravity system in the same operation. Vacuum tanks or collecting tanks are not required normally. Combined vacuum generators and forwarding pumps can be used for all size of systems. The size and number of combined vacuum generator and forwarding pumps to be used depends upon the required capacity. Combined vacuum generators and forwarding pumps have a small footprint compared to conventional vacuum stations and can be located in small ducts. A combined vacuum generator and forwarding pump is more power efficient than an ejector system, but a large number of combined vacuum generator and forwarding pumps would be more expensive to purchase and run than a comparable vacuum station based system.

Check and isolation valves

A check valve is installed in each vacuum pump suction line to maintain the vacuum in the system. Check valves are also fitted on the discharge from a vacuum discharge pump, and often are fitted on the service connection from an appliance.

Isolation valves are fitted to all forwarding and vacuum pumps to allow their removal without disrupting the system. Also they are fitted in strategic locations to enable sections of a system to be isolated for service. Isolation valves should be suitable for vacuum use and may be of the eccentric plug type or resilient face gate type and have a clean opening of not less than the nominal diameter of the pipe. Both check and isolation valves must be capable of withstanding 0.8 bar gauge vacuum, when open, and a differential pressure of 0.8 bar, when closed on a functioning system.

Pipework

Usually stainless steel and thermoplastic (ABS, HDPE, PVCu or MDPE) pipes are utilised for the construction of the vacuum pipelines, the selection of pipeline material is dependent upon its location and the characteristics of the waste water. All pipes used should be suitable for vacuum, and the minimum pressure rating for thermoplastics should be 10 bar but higher ratings shall be used if the pipe has an initial ovality; if progressive deformation or long term loss of strength due to high temperature is likely to occur. The velocities of water within the pipework and the resulting percussive effects at changes of direction lead to the requirement for such pressure rated pipe. Standard manufactured fittings are used where available; Y junctions for incoming branches should be 45° and reducers be concentric.

Generally, joints should be smooth and protrusion free to ensure full flow conditions.

Not all rubber ring pipe joints are suitable for vacuum systems, the manufacturer should supply a guarantee along with the test certification that the products are appropriate for vacuum drainage applications.

Design

Design requirements

The system should be designed to accept discharges from all appliances planned to be connected to the system. The designer should take into consideration any known possible future additions or modifications to the system to avoid future installation and operating constraints.

Design criteria

In order to design a vacuum drainage system the following basic parameters should be determined and obtained:

i. Service life expectancy
ii. Type of building
iii. Number of people the system is to serve
iv. Types, number and location of appliances to be connected
v. Wastewater temperature range (high temperature grey water discharges shall be specified concerning temperature, flow, batch volume and frequency)
vi. Ambient temperature range within which the system shall operate
vii. Minimum vacuum level required to operate the interface units and vacuum toilets
viii. Air to water ratios required for the interface units
ix. Air consumption of vacuum toilets
x. Permissible leakage factors.

The following parameters are required to calculate the pipe sizes and system layout. They should be determined by the designer and equipment supplier for each system:

i. Total wastewater flow
ii. Vacuum toilet flush frequency
iii. Dynamic losses between the vacuum station and the furthest appliance on each pipeline
iv. Static losses between the vacuum station and the furthest appliance on each pipeline
v. Required operational level of vacuum
vi. Required vacuum generator capacity
vii. Required forwarding pump capacity, if utilised
viii. Required collecting tank capacity, if utilised
ix. Pipe sizes
x. Vacuum recovery time.

Pipework design

Vacuum systems are designed to operate on two-phase air to liquid flows. The air in the pipework is not, as in a conventional horizontal gravity system, flowing above the wastewater but is entrained into the wastewater where its expansion propels the wastewater and lowers its bulk density. These factors enable the wastewater to behave more like a gas than a liquid and in particular flow uphill.

The strength of thermoplastics is affected by temperature. In industrial installations where high wastewater temperatures are anticipated, care must be taken in the selection of pipe materials. Wastewater temperatures greater than 70°C should be notified to the designer, so that the design can limit, by pipework design and buffer volume sizing, possible boiling due to pressures lower than atmosphere.

The pipes are installed in a near horizontal profile, without backfall (0.2-0.5% fall) to a suitably located vertical pipe. Once the vertical pipe (stack) is installed, all horizontal pipes may be connected at each level in the building in the void between floor and ceiling, subject to lift height restrictions. All service connections from the interface units could either be lifted to the pipeline in the ceiling above or dropped through the floor to the pipeline below. This makes installation one floor at a time possible which is particularly valuable in building refurbishment.

Preferably, connections to horizontal pipelines should be arrange so that the branch pipe enters from the top by way of a Y-fitting. As a minimum it shall connect into the top sector of the vacuum main pipeline contained within the angle of ±60° about the vertical axis. Vertical lift piping connecting to horizontal pipelines should enter from the top by way of a Y-fitting. Precautions should be taken, eg the use of a check valve suitable for vacuum drainage, to prevent filling the rise with wastewater by back surges. Horizontal piping connecting to vertical stacks should enter by way of single Y-branches. Multiple connections should be at staggered levels where practical.

For a larger building it is customary to divide the system into smaller sub-systems, possibly with a crossover, if not cost prohibitive, so that, in the event of failure of part of the system, each sub-system could operate as a standby for the other. The crossover pipework would be located between the vacuum station and pipework manifold of each sub-system. An isolation valve, the crossover valve, located within the crrossover pipework would, for normal operation, be closed.

Maintainability

System maintainability affects not only maintenance costs but also availability. The following aspects are the minimum that should be addressed as part of system design:

i. Fault finding procedures
ii. Access to all interface units, isolation valves, cleaning eyes, check valves and other items that need inspection and/or service
iii. Procedures for removal of interface units and their temporary effect on system performance, if any
iv. Maintenance schedules for interface units in relation to cycle frequency and endurance
v. Estimated repair or replacement times of interface units
vi. Maintenance schedule for vacuum station equipment
vii. Procedures for removal or repair of vacuum station equipment and their temporary effects on system performance, if any
viii. Estimated repair or replacement times for vacuum station equipment
ix. Precaution routines if system performance is temporarily lost or reduced
x. Training of maintenance personnel
xi. Recommended stocking of spare parts
xii. Estimated cost of maintenance per year.

References

The Environment Protection Agency (EPA) in USA.

Internet sites, and manufacturer's literature.

IoP/BRE/CIBSE Vacuum Drainage Systems Guidance (book and video).